HEAT

IN ITS

MECHANICAL APPLICATIONS.

A Series of Lectures

DELIVERED AT

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PREFACE.

The success which attended the Lectures on "The Practical Applications of Electricity," delivered in the Session 1882–83, induced the Council to make arrangements for a second series in the following Session. Another of the Great Sources of Power in Nature was selected, namely, "Heat," and this the lecturers were asked to treat in its Mechanical Applications—Mechanical Science being the primary object for which the Institution was founded. The six Lectures then given, in all cases gratuitously, are contained in the present volume. The Lecturers have well earned the thanks of their fellow members, and have conferred a benefit upon all Engineers and Scientists by their able discourses, often on recondite problems.

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HEAT IN ITS MECHANICAL APPLICATIONS.

15 November, 1883.

JAMES BRUNLEES, F.R.S.E., President,
in the Chair.

"The General Theory of Thermo-Dynamics."

By Professor Osborne Reynolds, F.R.S.[1]

In lecturing on any subject, it seems to be a natural course to begin with a clear explanation of the nature, purpose, and scope of the subject. But in answer to the question—What is thermo-dynamics? I feel tempted to reply—It is a very difficult subject, nearly, if not quite, unfit for a lecture. The reasoning involved is such as can only be expressed in mathematical language. But this alone should not preclude the discussion of the leading features in popular language. The physical theories of astronomy, light, and sound involve even more complex reasoning, and yet these have been rendered popular, to the very great improvement of the theories. Had it appeared to me that it was the necessity for mathematical expression which alone stood in the way of a general comprehension of this subject, I should have felt compelled to decline to deliver this lecture, honourable as I acknowledge the task to be.

What I conceive is the real difficulty in the apprehension of the leading features of thermo-dynamics is, that it deals with a thing or entity (if I may so call heat) which, although we can recognise and measure its effects, is yet of such a nature that we cannot with any of our senses perceive its mode of operation.

Imagine, for a moment, that clocks had been the work of Nature, and that the mechanism had been on such a small scale as to be imperceptible even with the highest microscope. The task of Galileo would then have been reversed; instead of inventing machinery to perform a certain object, his task would have been from the observed motion of the hands to have discovered the mechanical principles and actions of which these motions were

[1] The Lecturer was elected M. Inst. C.E. on the 4th of December following.

the result. Such an effort of reason would be strictly parallel to that which was required for the discovery of the mechanical principles and actions of which the phenomena of heat were the result.

In the imaginary case of the clock, the discovery might have been made in either of two ways. The scientific method would have been to have observed that the motion of the hands of the clock depended on uniform intermittent motion; this would have led to the principle of the uniformity of the period of vibrating bodies, and on this principle the whole theory of dynamics might have been founded. Such a theory would have been as obscure, but not more obscure, than the theory of thermo-dynamics. But there was another method in the case of timekeepers, the one by which the theory of dynamics was actually brought to light—namely, the invention of an artificial clock, the action of which could be seen, and, so to speak, understood. It was from the pendulum that the constancy of the periods of vibrating bodies was discovered, and from this followed the dynamical theories of astronomy, light, and sound. There is no great difficulty in the apprehension of these theories, because they do not call for the creation of a mental picture, but merely for the exaggeration or diminution of what we can actually see in the clock.

As regards the mechanical theory of heat, however, no visible mechanical contrivance was discovered or recognised which afforded an example of this action; apparently, therefore, the only possible method was the scientific method—namely, the discovery of the laws of its action from the observation of the phenomena of heat, and accepting these laws, without forming any mental image of the dynamical origin, was the only method open. This is what the present theory of thermo-dynamics purports to be.

But although the theory of thermo-dynamics may be said to have been discovered in the form in which it is now put forward, this is not quite true. For one of the discoverers of the second law, and the one who had priority over the others, worked by the aid of a definite mechanical hypothesis as to the actual molecular motions and forces on which the phenomena of heat depend, and many of the most important steps in the theory are solely to be attributed to his labours. But to return to the theory. This may be defined as including all the reasoning based on two perfectly general experimental laws, without any hypothesis as to the mechanical origin of heat. In this form thermo-dynamics is a purely mathematical subject and unfit for a lecture. But as no one who has studied the subject doubts for a moment the mechanical

origin of these laws, I shall be following the spirit, if not the letter of my subject, if I introduce a conception of the mechanical actions from which these laws spring. And this I shall do, although I should hardly have ventured, had it not been that, while considering this lecture, I hit on certain mechanical contrivances which afford sensible examples of the action of heat, in the same way as the pendulum is an example of the same principles as those involved in the phenomena of sound and light. These examples, thanks to the ready aid of Mr. Forster in constructing the apparatus, I am in a position to show you, and I am not without hope that these kinetic engines may in a great measure remove the source of obscurity on which I have dwelt.

The general action of heat to cause matter to expand, or to tend to expand, is sufficiently obvious and popular. That the expanding matter will do work is also sufficiently obvious, but the exact part which the heat plays in doing this work is very obscure.

It is now known that heat performs two, and it may well be said three, distinct parts in doing the work. These are—

(1) To supply the energy equivalent to the work done.
(2) To give the matter the elasticity which enables it to expand, *i.e.*, to convert the inert matter into an acting machine.
(3) To convey itself (*i.e.*, heat) in and out of the matter.

This third function is generally taken for granted in the theory of thermo-dynamics.

In order to make any use of thermo-dynamics, a knowledge of the experimental phenomena of heat is necessary; but as time will not permit of my entering largely into these, I have had some of the leading facts suspended as diagrams. One or two it will be well to mention.

Heat as a quantity is independent of temperature, the thermal unit taken being the amount of heat necessary to raise 1 lb. of water 1° Fahrenheit.

Temperature represents the intensity of heat in matter. Matter in most of its forms expands more or less uniformly as we add heat to it; hence the expansion of matter measures temperature. Gases such as air expand in absolute proportion to the heat added under a constant pressure.

Absolute temperature is an idea derived from the observed rate of contraction of gases; they would vanish to nothing with the temperature 461° below zero Fahrenheit. For the other phenomena I must refer to the diagrams as I proceed.

Our knowledge of these facts has been accumulating during the

last two hundred years, and it was in a very complete condition forty years ago, before thermo-dynamics was born. The birth of this science may be considered as the result of the recognition of work—motion against resistance—as a true measure of mechanical action, and of accumulated work or energy as the potency of all sources of power. These ideas have now become extremely popular, and all are able to recognise in the raised weight, the bent spring, the moving hammer, the same thing, energy, which is measured by the amount of work which can be derived from any of these sources.

Before the recognition of this means of measuring mechanical potency, any definite idea of the true mechanical action of heat was impossible, for we had not recognised the only mechanical action by which it can be measured.

In 1843 Joule [1] conclusively proved that, by the expenditure of about 772 ft.-lbs. a thermal unit of heat must be produced, provided all the work was spent in producing heat. The simplicity of the ideas here involved, and the completeness of Joule's proof, acted at once to render the first law popular. No language can be too strong in which to express the importance of this discovery; yet, as was long ago pointed out by Rankine,[2] the very popularity of Joule's law went a long way to obscure the fact that it did not constitute the sole foundation of the theory of thermo-dynamics. Before Joule's discovery it was recognised that heat acted a part in causing work to be performed. It was clearly seen that it was heat which caused the water to expand into steam, against the resistance of the engine, and the necessity of heat to cause matter to expand was recognised.

To make matter do work it was only necessary to heat it. It would expand, raising a weight; and since after doing its work the matter was still hot, it was supposed that the only necessity for the heat was to add increased elasticity to matter. It was seen that the heat that had once been used was so degraded in temperature that it could not be all used again. So that, although there was no idea that heat was actually consumed in doing the work, it was seen that for continuous work a continuous supply of heat at a high temperature was necessary. As regards the exact proportion of heat required for the supply of elasticity, to perform a certain quantity of work, fairly clear ideas prevailed. It was seen that this depended on various circumstances. These were formulated

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[1] Philosophical Magazine.

[2] "Engineer," June 28, 1867; also reprint of Rankine's Papers, p. 432.

by Carnot,[1] who in 1824 gave a formula, which is equivalent to our second law of thermo-dynamics, of which it was the parent.

Now this idea that heat merely caused work to be done was not absurd, as is sometimes supposed. Indeed we may say that the present popular idea that the whole heat is convertible into work is more erroneous than the old idea in the ratio of 10 to 1; because the old idea that the function of heat is to supply elasticity was right, as far as it went, and although the present idea that the function of heat is to supply energy from which the work is drawn is also right, yet in any known possible heat-engine ten times more heat is necessary for the purpose of giving elasticity to matter than is converted into work by elasticity. This error, which seems to be very general amongst those who have not made a special study of the subject, may, I think, be attributed—first, to the popularity of the first law of thermo-dynamics, and secondly to the fact that although the second law of thermo-dynamics is nothing more nor less than a statement of the proportion which the quantity of heat necessary to produce elasticity bears to the quantity which this elasticity will convert into work, yet that it is the invariable custom in stating this law to omit all attempt to explain the purpose which this excess of heat serves; the reason for this omission being that experiment only shows that this heat is necessary, and hence this is all that we have a right to say.

If such an error prevails it is only a popular error, for it certainly did not affect the progress of the science. No sooner did Joule's law become known than it was taken up by Rankine, who, in 1849,[2] published a complete theory of thermo-dynamics, based, as I have said, on a hypothetical constitution of matter. This was almost simultaneously followed by theories based on an improved form of Carnot's reasoning by Thomson[3] and Clausius.[4]

Rankine's theory was based on a hypothetical constitution of matter. He invented a system of molecular motions and constraints, which he called molecular vortices, and he then calculated the effects of these motions by the theory of mechanics. The fact that his reasoning was based on a hypothesis was considered by

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[1] "Reflexions sur la Puissance Motrice du Feu." Also W. Thomson, Trans. Roy. Soc. Edin., 1849.

[2] "On the Centrifugal Theory of Elasticity," &c., Trans. Roy. Soc. Edin., 1850. "On the Mechanical Action of Heat," Trans. Roy. Soc. Edin., 1850. Also reprint of Rankine's Papers.

[3] Berlin Academy, 1850. See also "Abhandlungen über die mechanische, Warmetheorie," Leipsic, 1864–7.

[4] Trans. Roy. Soc. Edin., 1857. Also reprint of Thomson's Papers.

many as a fault in his reasoning. But on the other hand the clear idea thus obtained, as to the reason of everything he was doing, gave him such an advantage over those who were working by experimental laws, of the meaning of which they would venture no opinion, that he was led to make discovery after discovery in advance of his competitors, while some of his discoveries are still beyond the reach of experiment.

There was, however, a difficulty Rankine had to face; some properties of matter were pointed out which his hypothetical matter did not possess. This was not much to be wondered at, for although Rankine had invented machinery which would account for the mechanical action of heat, there was no reason to suppose this to be the only machinery. Rankine, with a view to the difficult calculations he had to make, had chosen machinery as simple as possible. Instead, however, of trying to complicate it, he, yielding to the opinion of his cotemporaries, adopted the general conclusions to which it had led him as axiomatic laws, and so cut himself adrift from his hypothesis.

It comes to be, then, that the student of thermo-dynamics finds as a reason why we must pass a large amount of heat through his engine, besides that which is converted into work, he is to accept an axiomatic law as to the greatest possible amount that can be converted under the circumstances.

To tell a child who asks why he cannot have more food, that he can only have 6 oz. a day, would be considered cruel. So to tell a student who wants to know why, out of the ten million foot-lbs. in 1 lb. of coal, a steam-engine can only give one million as work, that he is only allowed $\frac{T_1 - T_2}{T_1 + 461}$, is cruel, yet this is all he can have from the theory of thermo-dynamics based on its experimental laws.

Rankine, when compelled to abandon his hypothesis as the foundation of his theory by the objections justly urged against it, pointed out the great disadvantage of a mechanical theory conveying no conception of the mechanical basis of its laws; and called on all those who taught the subject, to try and find some popular means of illustrating the second law.[1]

This call was made twenty years ago; but, I believe, up to the present time no such illustration has been forthcoming. When undertaking this lecture, I had no idea of such an illustration, and I did not intend to say much as to the reason of the second law.

[1] "Engineer," June 28, 1867.

But, as I have said, three weeks ago an idea occurred to me. It arose somewhat thus—

Heat acts in matter to transform heat into work by molecular mechanism. Having much studied the subject, I have in my mind a picture, right or wrong, of the mechanism, and the part which heat acts. The question occurred—Is there no way of making a machine such that, although the parts are in visible motion, and the energy transformed to work is visible energy, yet the energy supplied shall have the characteristics of heat-energy, and the machine shall act simply in virtue of the elasticity caused by the motion of its parts? The question had no sooner arisen than several ways of carrying out the idea presented themselves. The general idea of the mechanical condition which we call heat is, that the particles of matter are in active motion; but it is the motion of the individuals in a mob, with no common direction or aim. Rankine assumed the motion to be rotatory, but it now appears more probable that the motion in the particles is oscillatory, undulatory, rotatory, and all kinds of motion, whatsoever; so that the communication of heat to matter means the communication of internal agitation—mob agitation. If, then, we are to make a machine to act the part of hot matter, we must make a machine to perform its work in virtue of the communication of internal promiscuous motion amongst its parts. The action of heat-mechanism to do work is simply that of expansion of volume, or the increased effort to expand owing to increased agitation. I first tried to think of some working arrangements of small bodies which should forcibly expand when shaken; but it appeared that it would be much easier to effect a contraction. This was as good. As long as any definite alteration in shape could be produced against resistances by a definite amount of agitation in its parts, we should have a machine illustrating the action of the heat engine.

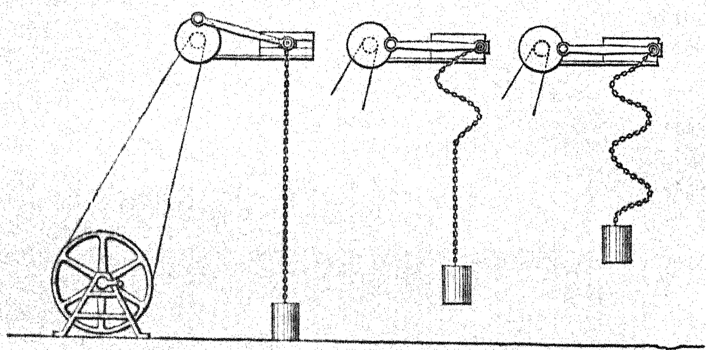
Suppose we want to raise a bucket from a well. Our best way is to pull or wind up the rope, but that is because the energy we employ is in a completely directable form. Suppose we had no such directable energy, but could only shake the rope, it having been first made fast at the top (Fig. 1, next page). Then, it being a heavy rope, a chain is better; suppose we shake the chain laterally, waves will run down the chain, and, if we go on shaking, the chain will assume a continuously changing sinuous form (Figs. 2 and 3); and, as the chain does not stretch, the bucket must be raised to allow for the sinuosities. The chain will have changed its mechanical character, and from being a tight line or tie in a vertical direction, will possess kinetic elasticity, that is,

elasticity in virtue of its motion, causing it to contract its vertical length.

The bucket will be raised, although not to the top of the well, and work will have been done in raising it, but the work spent in shaking the chain will be not only the equivalent of the work spent in raising the bucket, but also of all the kinetic agitation in the chain necessary to raise the bucket. Having raised the bucket as far as possible with a certain power of agitation, if the supply of agitation be cut off, then that already in the chain will sustain the bucket until it is destroyed by friction, when the bucket will gradually descend.

But if we want to do more work, to raise another bucket, we may take that which is raised off at the level at which it is raised; then, to get the chain down again, we must allow the agitation to

FIG. 1. FIG. 2. FIG. 3.

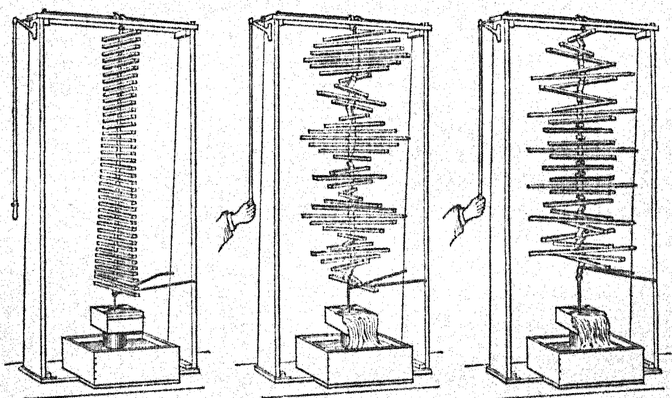


die out, *i.e.*, allow it to cool; then, attaching another bucket, to raise this, we shall again have to supply the same heat, perform the same work, *i.e.*, the work to raise the bucket, and the agitation-energy of the chain. Thus we see that the energy necessary to the working of the machine serves two purposes, it supplies the energy necessary to raise the bucket, and the energy necessary to convert the chain from an inextensible tie into an elastic contracting system, capable of raising the weight, neither of which portions of energy is again serviceable after the bucket has been raised. The one portion is already converted into work, and the other, although still in existence in the chain as energy, can only sustain the position of the chain. Before it could be used to do more work it must be got out of the chain and back again, which is just the thing you cannot do; we can get some of it out and some of it back, but not all.

It must not be supposed that this method of raising a bucket by shaking the rope is recommended as the best means. No one would dream of using it if we could get a direct pull, but that is nothing to the point. We are considering the action of heat, and we have limited ourselves to using energy of the same kind that heat supplies; that is, energy in the form of promiscuous agitation, absolutely without direction, so that the question is, how can we raise the bucket by shaking?

I feel that there is a childish simplicity about this illustration, that may at first raise the feeling of "Abana and Pharpar, rivers of Damascus," in the minds of some of my hearers, but, should this be the case, I have every confidence that calm reflection will have the same effect as on Naaman.

FIG. 4. FIG. 5. FIG. 6.



The case of the shaken rope, as I have put it, is no mere illustration of the action of heat, but an instance of the same application of the same principles. The sensible energy in the shaking rope only differs from the energy of heat (in a bar of metal) in the scale of the motion; we see the motion in the chain but not in the bar, not because the molecules of the bar are moving slower, but because the scale of motion is infinitely smaller. The temperature of the bar from absolute zero measures the mean square of the velocity of all its parts, multiplied by some constant depending on the mass of the parts which are moving together; so the mean square of the velocity of the chain multiplied by the weight per foot of the chain really represents the absolute temperature of the sensible energy in the chain.

The apparatus which I have on the table is an obvious adapta-

tion of the rope and the bucket. There are three different illustrations apparently very different in form, but all working by the same principle.

Here is the chain (Figs. 1, 2, 3), by the shaking of which (addition of promiscuous energy) a weight of 2 lbs. is raised 3 feet, or 6 foot-lbs. of work done; here is another sort of chain, a series of parallel horizontal bars of wood, connected and suspended by two strings (Figs. 4, 5, and 6). By giving a circular oscillation to the upper bar, the whole apparatus is set into a twisting motion (agitation); the strings are continually bent, and the vertical length of the whole system is shortened, and a weight of 10 lbs. or the bucket of the pump is caused to rise, raising water just as if we boiled water under the piston of a steam-engine. To get the bucket down again for another stroke, we must quiet (or cool) the chain, just as we must condense the steam, and the energy taken out of the chain in quieting corresponds exactly with the heat that must be taken out of the steam in order to condense it.

The waves of the sea constitute a source of energy in the form of sensible agitation; but this energy cannot be used to work continuously one of these kinetic-machines, for exactly the same reason as the heat in the bodies at the mean temperature of the earth's surface cannot be used to work heat-engines. A chain attached to a ship's mast in a rough sea would become elastic with agitation, but this elasticity could not be used to raise cargo out of the hold, because it would be a constant quantity as long as the roughness of the sea lasted.

In practical mechanics we have no source of energy consisting of sensible agitation, besides the waves of the sea; so that there has been no demand for these kinetic engines to transform sensible mob-energy into work; had there been, I might have patented my idea, though probably it would have long ago been discovered. But there has been a demand for what we may call sensible kinetic elasticity, to perform for sensible motion the part which the heat elasticity performs in the thermometer, and for this purpose the principle of the kinetic machine was long ago applied by Watt. The common governor of a steam engine acts by kinetic elasticity, which elasticity, depending on the speed at which the governor is driven, enables the governor to contract as the speed increases. The motion of the governor is not of the form of promiscuous agitation, but, though systematic, all the motion is at right angles to the direction of operation, so that the principle of its action is the same.

The kinetic elasticity of the governor performs the same part as the heat elasticity in the matter of the thermometer; the first measures by contraction the velocity of the engine, and the other measures by expansion the velocity of the molecules of the matter by which it is surrounded, so that we now see that while measuring the speed of sensible revolution, we are performing on a different scale the same operation as measuring the temperature of bodies which depends on the molecular velocities, and that quite unconsciously we have constructed instruments to perform the two similar operations which act by means of the same mechanical action, namely, kinetic elasticity.

These kinetic examples of the action of heat must not be expected to simplify the theory, except in so far as they give the mind something definite to grasp; what they do is to substitute something we can see for what we can barely conceive.

The theory of thermo-dynamics can be deduced from any one of these kinetic examples by the application of the principles of mechanics; such application involves complex dynamical reasoning, such as can only be executed by the aid of mathematics, and would be altogether unfit to introduce into a lecture. I shall therefore pass on to some considerations resulting from the theory of thermo-dynamics.

The discovery of the two laws have enabled us to perfect and complete our experimental knowledge of the phenomena of heat. But probably the greatest practical use is that these two laws enable us to calculate with certainty, from the experimental properties of any matter, the extreme potency of any source of power.

Thus we find by experiment that a pound of coal burnt in a furnace yields fourteen to sixteen thousand thermal units of heat. The first law, Joule's law, tells us at once that this is equivalent to from 11,000,000 to 13,000,000 foot-lbs. of energy. But this is not, as seems to be generally supposed, the power of coal. The second law of thermo-dynamics tells us that in order that this energy might be realised, it must be capable of being developed at an infinite temperature, whereas we know that this cannot be the case; and there is a growing idea that the temperature at which coal will burn is not so extremely high, about 3,000° Fahrenheit. Taking this temperature, and assuming the temperature of the atmosphere to be 60°, we have for the proportion of the heat of coal, that we could with a perfect engine call power, $\frac{2940}{3461}$, about 80 per cent., or from 9,000,000 to 11,000,000 foot-lbs.

Again, we know the heat properties of all known liquids and

gases, so that we can, by the second law, tell the greatest possible proportion of the heat received, which can be converted into power by any of these agents.

In the steam-engine, for instance, we see that the present limits of art restrict the temperatures absolutely to 400°, and practically the limits are much less; while the lowest temperature that can be worked to in a condenser is 100°. Then, as the limit to the possibility, we have one-third as the greatest proportion, or three out of the nine million foot-lbs.

The greatest actual achievement by Mr. Perkins has been about two millions, while the best engines in use only give us a little over one million, or about one-ninth of the possible realizable portion between 3,000° and the mean temperature of the earth's surface.

I cannot here enter upon these, but the reasons why higher temperatures cannot be used in the steam-engine are obvious enough.

The same reasons do not apply to hot air as an agent. This may be worked at much greater temperatures; and about thirty years ago, as soon as it appeared from the science of thermo-dynamics that the limit of efficiency depended on the range of temperature, attention was much directed to air as a substitute for steam. The attempts then made failed through what were then called practical, or art difficulties.

Just at the present time the possibility of other heat-engines than steam-engines is again come to the front; and as this is so, it seems desirable to call attention to a circumstance connected with heat-engines which has as yet occupied quite a subordinate place in the theory of heat-engines. This is the law as to the rate at which heat can be made to do work by an agent, such as steam or air. The greatest possible efficiency of the agent, *i.e.*, the proportion which the work done bears to the mechanical equivalent of the heat spent, is a matter of fundamental importance; but the rapidity with which the heat can be so transformed with a given amount of apparatus, as an engine of a given weight, is a matter of at least as great importance.

Which would be the best engine for a steamboat; one that would develop 20 HP. for every ton gross weight, consuming 2 lbs. of coal per HP. per hour, or one that only gave 2 HP. per ton weight, and only consumed 1 lb. of coal? Unquestionably the former; yet hitherto the question of heat-economy has been considered theoretically, to the exclusion of time-economy. Yet the latter forms a legitimate part of the subject of thermo-

dynamics, and has played a greater part in the selection of steam as the fittest agent than the consideration of the heat-economy.

In the theory of thermo-dynamics it is assumed that the working agent, be it water or any other, can be heated up and cooled down at pleasure, without any consideration as to the time taken for these operations, which are considered to be mere mechanical details.

Yet in the science of heat a great amount of labour has been spent; a great amount of knowledge gained as to the rate at which heat will traverse matter. And more than this; it is well known that heat cannot be made to enter and leave matter without a certain loss of power, *i.e.*, a certain lowering of the working range of temperature. It is by heat that heat is carried into the substance; and hence, as I have indicated, there is a third law of thermo-dynamics relative to this transmission. Heat only flows down the gradient of temperature, and in any particular substance the rate at which heat flows is proportional to the gradient of temperature. Hence to get the heat from the source or furnace into the working substance a certain time must be consumed, and this time diminishes as the difference of temperature of the furnace and the working substance increases.

The examples of the kinetic engines which I have shown you well illustrate this. If we shake the end of a chain, the wriggle passes along the chain at a given speed. It appears that an interval must elapse between the first shaking of the chain and the establishment of sufficient agitation to move the bucket; a further interval before the bucket is completely raised; and further still, another interval must elapse before the chain can be cooled again for another stroke; so that this kinetic engine will only work at a given rate. I can increase this rate by shaking harder, but then I expend more energy in proportion to the work done.

This exactly corresponds with what goes on in the steam-engine, only, owing to the agent water being heated, expanded, and cooled severally in the boiler, cylinder and condenser, the connection is somewhat confused.

But it is clear that for every HP. something like 15 million foot-pounds of power have to pass from the furnace into the boiler. As out of this 15 we cannot use more than 2 million, the remaining 13 are available for forcing the heat from the products of combustion into the water, and out of the steam into the condensing water, and they are usefully employed for this purpose.

The boilers are made small enough to produce sufficient steam,

and this size is determined by the difference of the internal temperature of the gases in the furnace and the water in the boiler, and whatever diminishes this difference would necessarily increase the size of the heating surface, *i.e.*, the weight of the engine. The power which this difference of temperature represents cannot be realised in the steam-engine, so that it is most usefully employed in diminishing the necessary size of the boiler. Still it is an important fact to recognise that our present steam-engines require the expenditure of more than five times as much of the power of the heat (not of the heat) in getting the heat into the working substance as in performing the actual operation. This loss of power does not so much occur in the resistance of the metal which separates the furnace from the water as in the resistance of the gases. Gas is a very bad conductor; and though a thin layer adjacent to the plates is always considerably cooled, little further cooling goes on until, by the internal currents, this layer is removed, and a fresh hot layer substituted in its place.

Similar resistance would occur inside the boiler between the water and the hot plate, nay does occur, until the water begins to boil, but then the evaporation of the water takes place at the hot surface, and every particle of water boiled absorbs a great deal of heat, which leaves the surface in the form of bubbles, allowing fresh water to come up.

If we had air inside the boiler instead of water, we should require from five to ten times the surface to carry off the same heat, which is a sufficient reason why what are called hot-air engines cannot answer, even did not the same argument hold with enormously greater force in the condenser.

Steam is as bad a conductor of heat as air as long as it does not condense, but, in condensing, steam will conduct heat to a cold surface at an almost infinite rate, for as the steam comes up to the surface it is virtually annihilated, leaving room for fresh steam to follow, which it will do if necessary with the velocity of sound. If, however, there is the least incondensable air in the steam this will be left as a layer against the fresh steam. Some years ago I made some experiments on this subject, which showed that 5 or 10 per cent. of air in the steam would virtually prevent condensation.

If a flask be boiled till all the air is out, and nothing but pure steam is left, and if the flask be then closed and a few drops of cold water introduced, the pressure instantly falls to zero, though it immediately recovers from the boiling of the water in the flask. If now a little air be admitted, and allowed to mix with the steam, the few drops of water produce scarcely any effect.

The facility with which steam carries heat to a cold surface is both an enormous advantage and some drawback; as compared with air it is an enormous advantage in enabling the steam to be cooled in the condenser. But during the working of the steam in the cylinder, when the steam is wanted to keep its heat, the facility with which it condenses is a great drawback, and necessitates the keeping of the cylinder hotter than the steam by a steam-jacket. For this part of its work the non-conductivity of incondensable air is a great advantage.

In dwelling thus on the conducting powers of air and steam, my purpose has been to prepare the way for a few remarks I wish to make on another form of heat-engine—the engine in which the heat is generated in the working substance itself.

The combustion-engine, in the form of the cannon, is the oldest form of heat-engine. Here the chemically separate elements in the form of gunpowder are the working substances put into the cylinder; they take in with them the potential energy of chemical separation, which by means of a spark take the kinetic form of heat. Here there is no conduction, the kinetic elasticity propels the shot, and all the heat over and above that used in imparting energy to the shot is lost. The advantages of this form of engine are two. There is no time necessary for conduction, and as the gas generated is not condensable, there is little loss of heat by conduction to the cold metal.

These two advantages are very great, but I should not have mentioned them in reference to guns were it not that there appears to be the dawning of an idea of taming this form of engine so as to substitute it for the steam-engine. To do this it is necessary to introduce coal or coal-gas;—and oxygen in the form of air in place of gunpowder. The thermo-dynamic theory applied to such engines shows that they should possess great advantages over the steam-engine in point of economy. And the considerations I have brought forward as to the loss of the power of heat in the transference of heat from the furnace to the boiler seem to promise such engines an enormous advantage in rate of work, while the substitution of a non-condensable gas for steam in the cylinder seems to get over the art-difficulty of making cylinders to work under high temperatures. We cannot expect any piston to work in a cylinder of over 300° or 400° temperature, but with non-condensing gases the cylinder may be kept cool with little cooling effect on the gases contained in it, even if the temperature of these is 3,000°. This will be the case if the gas in the cylinder is not in a violent state of internal agita-

tion, but it should be remembered that all internal currents much facilitate the conveyance of heat to the walls.

There is one drawback shown by the theory of these engines. The simple expansion of the gases resulting from combustion is not sufficient to cool them to anything like the temperature of 60°, and to get the greatest economy some of the remaining heat should be used to heat the fresh charge. To do this, however, would necessitate the extraction of the heat from one mass of gas to communicate it to another, which would introduce all the difficulties of the boiler increased by having gas instead of water.

But even wasting this heat, the theory still shows a large margin of economy for such engines over the present performance of steam-engines, a margin which is said to have been already realised in the gas-engine, which is a form of combustion-engine in a high state of efficiency. Now, by means of Dowson gas, Messrs. Crossley seem to have obtained 2,000,000 out of the 10,000,000 ft.-lbs. in 1 lb. of coal. Further accomplishment in this direction is a question of art; but while on all other hands science shows impassable barriers not far in advance of the present achievements of art, in this direction thermo-dynamics extended to include the rate of operation shows no known barriers; while the fact that, as gas-engines, this system of combustion heat-engines has already established a footing assures them continual improvement.

In conclusion I would say, by way of caution, that the theory of thermo-dynamics does not lead to the inference, which seems to be generally held by those who have only realised the first law of the science, that the steam-engine is a semi-barbarous machine, wasting more than it uses, very well for those who know no science, but only waiting until those better educated have time to turn their attention to practical matters, and then to give place to something much better. Thermo-dynamics shows us not the faults but the perfections of the steam-engine in which there is no waste of power, since all is used either in doing work or in promoting the rate at which the work can be done. Next to the watch the steam-engine is the highest development of mechanical art, and the science of thermo-dynamics may be said to be the result of the study of the steam-engine.

On the motion of the President a cordial vote of thanks to Professor Reynolds was carried by acclamation, for his valuable contribution to a most important subject.

6 December, 1883.

JAMES BRUNLEES, F.R.S.E., President,
in the Chair.

"On the Generation of Steam, and the Thermodynamic Problems Involved."

By William Anderson, M. Inst. C.E.

It will not be necessary to commence this lecture by explaining the origin of fuel; it will be sufficient if I remind you that it is to the action of the complex rays of the sun upon the foliage of plants that we mainly owe our supply of combustibles. The tree trunks and branches of our forests, as well as the subterranean deposits of coal and naphtha, at one time formed portions of the atmosphere in the form of carbonic acid gas; that gas was decomposed by the energy of the solar rays, the carbon and the oxygen were placed in positions of advantage with respect to each other—endowed with Potential Energy; and it is my duty this evening to show how we can best make use of these relations, and by once more combining the constituents of fuel with the oxygen of the air, reverse the action which caused the growth of the plants, that is to say, by destroying the plant reproduce the heat and light which fostered it.

The energy which can be set free by this process cannot be greater than that derived originally from the sun, and which, acting through the frail mechanism of green leaves, tore asunder the strong bonds of chemical affinity wherein the carbon and oxygen were united, converting the former into the ligneous portions of the plants and setting the latter free for other uses. The power thus silently exerted is enormous; for every ton of carbon separated in twelve hours necessitates an expenditure of energy represented by at least 1,058 HP., but the action is spread over an enormous area of leaf surface, rendered necessary by the small proportion of carbonic acid contained in the air, by measure only $\frac{1}{2000}$ part, and hence the action is silent and imperceptible.

It is now conceded on all hands that what is termed heat is the energy of molecular motion, and that this motion is convertible into various kinds, and obeys the general laws relating to motion.

Two substances brought within the range of chemical affinity unite with more or less violence; the motion of transition of the particles is transformed, wholly or in part, into a vibratory or rotatory motion, either of the particles themselves or of the inter-atomic ether; and according to the quality of the motions we are, as a rule, besides other effects, made conscious of heat, or light, or of both. When these emanations come to be examined they are found to be complex in the extreme, intimately bound up together, and yet capable of being separated and analysed.

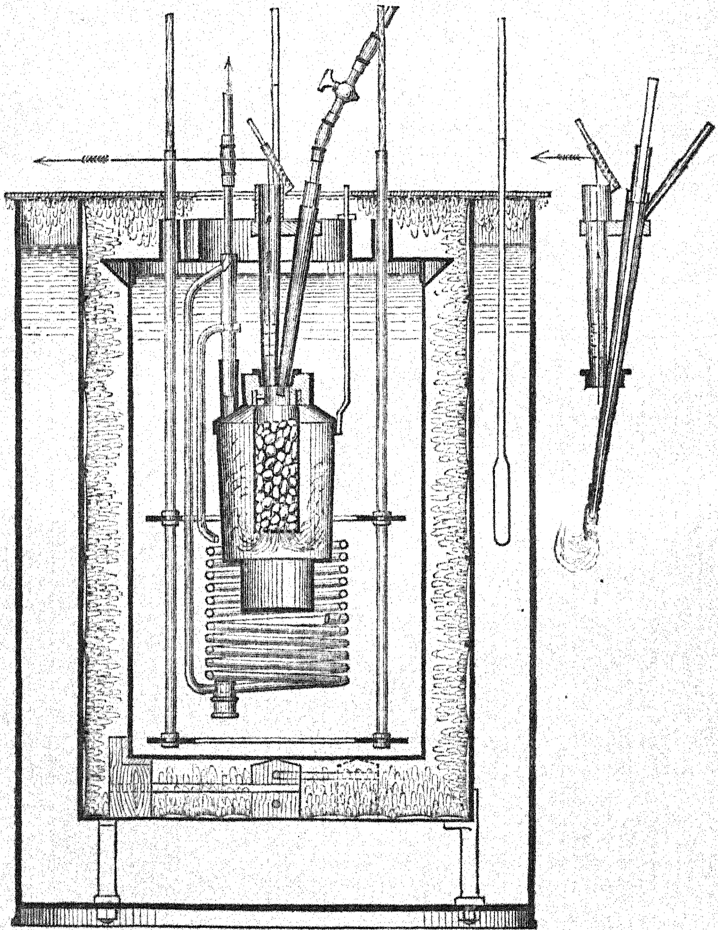
As soon as the law of definite chemical combination was firmly established, the circumstance that changes of temperature accompanied most chemical combinations was noticed, and chemists were not long in suspecting that the amount of heat developed or absorbed by chemical reaction should be as much a property of the substances entering into combination as their atomic weights. Solid ground for this expectation lies in the dynamic theory of heat. A body of water at a given height is competent, by its fall, to produce a definite and invariable quantity of heat or work, and in the same way two substances falling together in chemical union acquire a definite amount of kinetic energy, which, if not expended in the work of molecular changes, may also, by suitable arrangements, be made to manifest a definite and invariable quantity of heat.

At the end of last century Lavoisier and Laplace, and after them, down to our own time, Dulong, Despretz, Favre and Silbermann, Andrews, Berthelot, Thomsen and others, devoted much time and labour to the experimental determination of the heat of combustion and the laws which governed its development. Messrs. Favre and Silbermann, in particular, between the years 1845 and 1852, carried out a splendid series of experiments by means of the apparatus partly represented in Fig. 1, which is a drawing one-third the natural size of the calorimeter employed.

It consisted essentially of a combustion chamber formed of thin copper, gilt internally. The upper part of the chamber was fitted with a cover through which the combustible could be introduced, with a pipe for a gas jet, with a peep-hole closed by adiathermanous but transparent substances, alum and glass, and with a branch leading to a thin copper coil surrounding the lower part of the chamber and descending below it. The whole of this portion of the apparatus was plunged into a thin copper vessel, silvered internally and filled with water, which was kept thoroughly mixed by means of agitators. This second vessel stood inside a third one the sides and bottom of which were covered with the skins of swans

with the down on, and the whole was immersed in a fourth vessel filled with water, kept at the average temperature of the laboratory. Suitable thermometers of great delicacy were provided, and all manner of precautions were taken to prevent loss of heat.

Fig. 1.



Calorimeter of Favre and Silbermann, 1845–1852.

Scale ½.

It is impossible not to admire the ingenuity and skill exhibited in the details of the apparatus, in the various accessories for

generating and storing the gases used, and for absorbing and weighing the products of combustion; but it is a matter of regret that the experiments should have been carried out on so small a scale. For example, the little cage which held the solid fuel tested was only $\frac{5}{8}$ inch diameter by barely 2 inches high, and held only 38 grains of charcoal, the combustion occupying about sixteen minutes.

Favre and Silbermann adopted the plan of ascertaining the weight of the substances consumed by calculation from the weight of the products of combustion. Carbonic acid was absorbed by caustic potash, so also was carbonic oxide, after having been oxidised to carbonic acid by heated oxide of copper, and the vapour of water was absorbed by concentrated sulphuric acid. The adoption of this system showed that it was, in any case, necessary to analyse the products of combustion in order to detect imperfect action. Thus, in the case of substances containing carbon, carbonic oxide was always present to a variable extent with the carbonic acid, and corrections were necessary in order to determine the total heat due to the complete combination of the substance with oxygen.

Another advantage gained was that the absorption of the products of combustion prevents any sensible alteration in the volumes during the process, so that corrections for the heat absorbed in the work of displacing the atmosphere were not required.

The experiments on various substances were repeated many times. The mean results for those in which we are immediately interested are given in Table I.

Comparison with later determinations have established their substantial accuracy.

The general conclusion arrived at is thus stated :—"As a rule there is an equality between the heat disengaged or absorbed in the acts, respectively, of chemical combination or decomposition of the same elements, so that the heat evolved during the combination of two simple or compound substances is equal to the heat absorbed at the time of their chemical segregation." This law is, however, subject to some apparent exceptions. Carbon burned in protóxide of nitrogen, or laughing gas, N_2O, produces about 38 per cent. more heat than the same substance burned in pure oxygen, notwithstanding that the work of decomposing the protoxide of nitrogen has to be performed.

In marsh gas, or methane, $C\,H_4$, again, the energy of combustion is considerably less than that due to the burning of its carbon and hydrogen separately. These exceptions probably arise from the

TABLE I.—SUBSTANCES ENTERING into the COMPOSITION of FUEL.[1]

—	Symbol and Atomic Weight,		Heat evolved in the Combustion of 1 lb. of Fuel.	
	Before Combustion.	After Combustion.	In British Thermal Units.	In Pounds of Water Evaporated from, and at, 212°.
Hydrogen burned in oxygen	H . . 1	H_2O . 18	62,032	64·21
Carbon burned to carbonic oxide	C . . 12	CO . 28	4,451	4·61
Carbon burned to carbonic acid	C . . 12	CO_2 . 44	14,544	15·06
Carbonic oxide burned to carbonic acid	CO . 28	CO_2 . 44	4,326	4·48
Olefiant gas (ethylene) burnt in oxygen	C_2H_4 . 28	$\begin{Bmatrix}2CO_2\\2H_2O\end{Bmatrix}$ 124	21,343	22·09
Marsh gas (methane) burnt in oxygen	CH_4 . 16	$\begin{Bmatrix}CO_2\\2H_2O\end{Bmatrix}$ 80	23,513	24·34

Composition of air $\begin{cases}\text{by volume } 0{\cdot}788\ N + 0{\cdot}197\ O + 0{\cdot}001\ CO_2 + 0{\cdot}014\ H_2O\\ \text{by weight } 0{\cdot}771\ N + 0{\cdot}218\ O + 0{\cdot}009\ CO_2 + 0{\cdot}017\ H_2O\end{cases}$

circumstance that the energy of chemical action is absorbed to a greater or less degree in effecting molecular changes as for example, the combustion of 1 lb. of nitrogen to form protoxide of nitrogen results in the absorption of 1,157 units of heat.

Berthelot states, as one of the fundamental principles of thermochemistry, "that the quantity of heat evolved is the measure of the sum of the chemical and physical work accomplished in the reaction;" and such a law will no doubt account for the phenomena above noted.

The equivalent heat of combustion of the compounds we have practically to deal with has been experimentally determined, and therefore constitutes a secure basis on which to establish calculations of the calorific value of fuel; and in doing so, with respect to substances composed of carbon, hydrogen, and oxygen, it is

[1] Mr. Deering, of the Chemical Department of the Royal Arsenal, Woolwich, has pointed out that the heat of combustion of hydrogen given in the Table includes the heat liberated in condensing the vapour of water to the liquid form, but that in furnaces the water produced retains the gaseous state, and consequently the units of heat available are so much less. One pound of hydrogen burns to 9 pounds of water, which, if condensed at 212°, would yield $9 \times 966 = 8{,}694$ units of heat; hence, in the gaseous state, the available heat would be $62{,}032 - 8{,}694 = 53{,}338$ units, and the general formula would become—

$$\text{Heat of combustion} = 14{,}544 \left\{C + 3{\cdot}67\left(H - \frac{O}{8}\right)\right\}.$$

convenient to reduce the hydrogen to its heat-producing equivalent of carbon. The heat of combustion of hydrogen being 62,032 units, that of carbon 14,544 units, it follows that 4·265 times the weight of hydrogen will represent an equivalent amount of carbon. With respect to the oxygen, it is found that it exists in combination with the hydrogen in the form of water, and, being combined already, abstracts its combining equivalent of hydrogen from the efficient ingredients of the fuel; and hence hydrogen, to the extent of $\frac{1}{8}$ of the weight of the oxygen, must be deducted. The general formula then becomes—

$$\text{Heat of combustion} = 14{,}544 \left\{C + 4{\cdot}265\left(H - \frac{O}{8}\right)\right\},$$

and water evaporated from and at 212°, taking 966 units as the heat necessary to evaporate 1 lb. of water,

$$\text{lb. evaporated} = 15{\cdot}06 \left\{C + 4{\cdot}265\left(H - \frac{O}{8}\right)\right\}$$

carbon, hydrogen, and oxygen being taken at their weight per cent. in the fuel. Strictly speaking, marsh gas should be separately determined.

It often happens that available energy is not in a form in which it can be applied directly to our needs. The water flowing down from the mountains in the neighbourhood of the Alpine tunnels was competent to provide the power necessary for boring through them, but it was not in a form in which it could be directly applied. The kinetic energy of the water had first to be changed into the potential energy of air under pressure, then, in that form, by suitable mechanism, it was used with signal success to disintegrate and excavate the hard rock of the tunnels.

The energy resulting from combustion is also incapable of being directly transformed into useful motive power; it must first be converted into the potential force of steam or air at high temperature and pressure, and then applied, by means of suitable heat-engines, to produce the motions we require. It is probably to this circumstance that we must attribute the slowness of the human race to take advantage of the energy of combustion. The history of the steam-engine hardly dates back two hundred years, a very small fraction of the centuries during which man has existed, even since historic times.

The apparatus by means of which the potential energy of fuel with respect to oxygen is converted into the potential energy of steam, we call a steam boiler; and although it has neither cylinder nor piston, crank, nor fly-wheel, I claim for it that it is a veritable

heat-engine, because it transmits the undulations and vibrations caused by the energy of chemical combination in the fuel to the water in the boiler; these motions expend themselves in overcoming the liquid cohesion of the water and imparting to its molecules that vigour of motion which converts them into the molecules of a gas which, impinging on the surfaces which confine it and form the steam space, declare their presence and energy in the shape of pressure and temperature.

A steam pumping-engine, which furnishes water under high pressure to raise loads by means of hydraulic cranes, is not more truly a heat-engine than a simple boiler, for the latter converts the latent energy of fuel into the latent energy of steam, just as the pumping engine converts the latent energy of steam into the latent energy of the pumped-up accumulator or the hoisted weight.

If I am justified in taking this view, then I am justified in applying to my heat-engine the general principles laid down in 1824 by Sadi Carnot, namely, that the proportion of work which can be obtained out of any substance working between two temperatures depends entirely and solely upon the difference between the temperatures at the beginning and end of the operation; that is to say, if T be the higher temperature at the beginning, and t the lower temperature at the end of the action, then the maximum possible work to be got out of the substance will be a function of $(T - t)$.

The greatest range of temperature possible or conceivable is from the absolute temperature of the substance at the commencement of the operation down to absolute zero of temperature, and the fraction of this which can be utilized is the ratio which the range of temperature through which the substance is working bears to the absolute temperature at the commencement of the action. If $W =$ the greatest amount of effect to be expected, T and t the absolute temperatures, and H the total quantity of heat (expressed in foot-pounds or in water evaporated, as the case may be), potential in the substance at the higher temperature T at the beginning of the operation, then Carnot's law is expressed by the equation—

$$W = H\left(\frac{T - t}{T}\right).$$

I will illustrate this important doctrine in the manner which Carnot himself suggested.

Fig. 2 represents a hillside rising from the sea. Some distance up there is a lake, L, fed by streams coming down from a

still higher level. Lower down on the slope is a millpond, P, the tail race from which falls into the sea. At the millpond is esta-

FIG. 2.

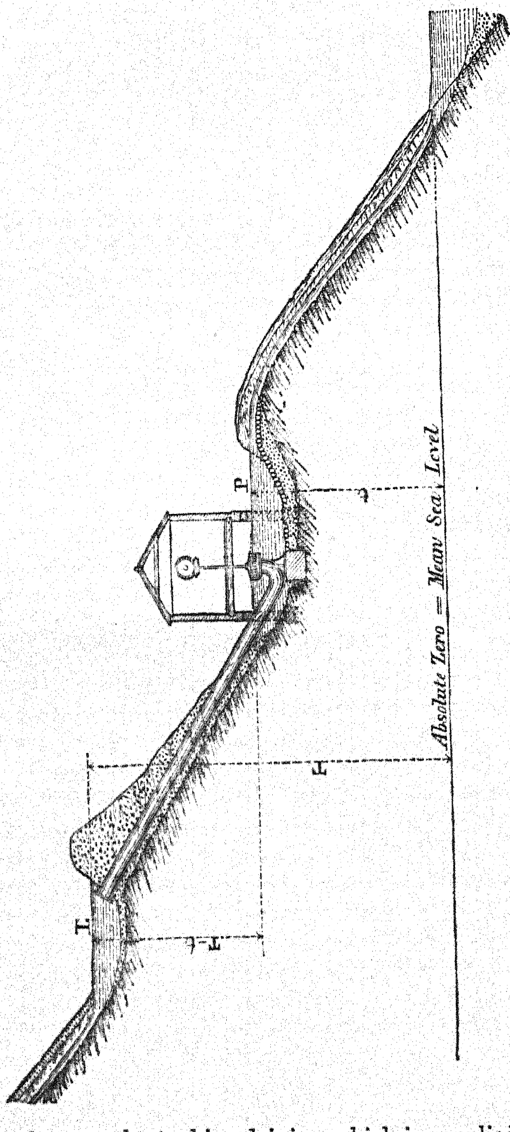


ILLUSTRATION OF CARNOT'S DOCTRINE, 1824.

blished a factory, the turbine driving which is supplied with water by a pipe descending from the lake L. Datum is the mean sea-level;

the level of the lake is T, and of the millpond t. Q is the weight of water falling through the turbine per minute. The mean sea-level is the lowest level to which the water can possibly fall; hence its greatest potential energy, that of its position in the lake, $= Q\,T = H$. The water is working between the absolute levels T and t; hence, according to Carnot, the maximum effect, W, to be expected is—

$$W = H\left(\frac{T - t}{T}\right),$$

but $$H = Q\,T \therefore W = Q\,T\left(\frac{T - t}{T}\right)$$

$$W = Q\,(T - t).$$

that is to say, the greatest amount of work which can be expected is found by multiplying the weight of water into the clear fall, which is, of course, self-evident.

Now, how can the quantity of work, to be got out of a given weight of water, be increased without in any way improving the efficiency of the turbine? In two ways.

1. By collecting the water higher up the mountain, and by that means increasing T.

2. By placing the turbine lower down, nearer the sea, and by that means reducing t.

Now the sea-level corresponds to the absolute zero of temperature, and the heights T and t to the maximum and minimum temperatures between which the substance is working, therefore similarly, the way to increase the efficiency of a heat-engine, such as a boiler, is to raise the temperature of the furnace to the utmost, and reduce the heat of the smoke to the lowest possible point.

It should be noted, in addition, that it is immaterial what liquid there may be in the lake; whether water, oil, mercury, or what not, the law will equally apply, and so in a heat-engine the nature of the working substance, provided that it does not change its physical state during a cycle, does not affect the question of efficiency with which the heat being expended is utilized. To make this matter clearer, and give it a practical bearing, I will give the symbols a numerical value, and for this purpose I will, for the sake of simplicity, suppose that the fuel used is pure carbon, such as coke or charcoal, the heat of combustion of which is 14,544 units, that the specific heat of air, and of the products of combustion at constant pressure, is 0·238, that only sufficient air is passed through the fire to supply the quantity of oxygen theoretically required for the combustion of the carbon, and that the temperature of the air

is at 60° Fahrenheit = 520° absolute. The symbol T represents the absolute temperature of the furnace, a value which is easily calculated in the following manner:—

1 lb. of carbon requires $2\frac{2}{3}$ lbs. of oxygen to convert it into carbonic acid, and this quantity is furnished by 12·2 lbs. of air, the result being 13·2 lbs. of gases, heated by 14,544 units of heat due to the energy of combustion; therefore

$$T = 520° + \frac{14{,}544 \text{ units}}{13{\cdot}2 \text{ lbs.} \times 0{\cdot}238} = 5{,}150° \text{ absolute.}$$

The lower temperature t we may take as that of the feed-water, say at 100° or 560° absolute, for by means of artificial draught and sufficiently extending the heating surface, the temperature of the smoke may be reduced to very nearly that of the feed-water.

Under such circumstances the proportion of heat which can be realised is $= \frac{5150° - 560°}{5150} = 0{\cdot}891$; that is to say, under the extremely favourable, if not impracticable conditions assumed, there must be a loss of 11 per cent.

Next, to give a numerical value to the potential energy H to be derived from a pound of carbon, calculating from absolute zero, the specific heat of carbon being 0·25, and absolute temperature of air 520°.

		Units.
1 lb. carbon × 0·25 × 520	=	130
12·2 lbs. of air × 0·238 × 520	=	1,485
Heat of combustion	=	14,544
		16,159
Deduct heat equivalent to work of displacing atmosphere by products of combustion raised from 60° to 100°, or from 149·8 cubic feet to 161·3 cubic feet .		32
Total units of heat available . .		16,127

equal to 16·69 lbs. of water evaporated from and at 212°. Hence the greatest possible evaporation from and at 212° from a pound of carbon—

$$W = \frac{16{,}159 \text{ u.} \times 0{\cdot}891 - 32 \text{ u.}}{966 \text{ u.}} = 14{\cdot}87 \text{ lbs.}$$

I will now take a definite case, and compare the potential energy of a certain kind of fuel with the results actually obtained. For this purpose the boiler of the 8-horse portable engine, which gained

the first prize at the Cardiff Show of the Royal Agricultural Society in 1872, will serve very well, because the trials, all the details of which are set forth very fully in Vol. ix. of the Journal of the Society, were carried out with great care and skill by Sir Frederick Bramwell and the late Mr. Menelaus; indeed, the only fact left undetermined was the temperature of the furnace, an omission due to the want of a trustworthy pyrometer, a want which has not been satisfied to this day.[1] The data necessary for our purpose are:—

Steam-pressure 80 lbs., temperature	324° = 784° absolute.
Mean temperature of smoke	389° = 849° „
Water evaporated per 1 lb. of coal, from and at 212°	11·83 lbs.
Temperature of the air	60° = 520° „
„ of feed-water	209° = 669° „
Heating-surface	220 square feet.
Grate-surface	3·29 feet.
Coal burnt per hour	41 lbs.

The fuel used was a smokeless Welsh coal, from the Llangennech collieries. It was analysed by Mr. Snelus, of the Dowlais Ironworks, and in Table II. are exhibited the details of its

[1] In the fifty-second volume of our Proceedings (1877–78), page 154, will be found a remarkable experiment on the evaporative power of a vertical boiler with internal circulating pipes. The experiment was conducted by Sir Frederick Bramwell and Dr. Russell, and is remarkable in this respect, that the quantity of air admitted to the fuel, the loss by convection and radiation, and the composition of the smoke were determined.

The facts observed were as follows:—

Steam pressure 53 lbs. = 300·6° F.

	lbs.
Fuel—Water in coke and wood	26·08
Ash	10·53
Hydrogen, oxygen, nitrogen, and sulphur	7·18
Total non-combustible	43·79
Carbon, being useful combustible	194·46
Total fuel	238·25

Air per pound of carbon	17⅛ lbs.
Time of experiment	4 h. 12 min.
Water evaporated from 60° into steam at 53 lbs. pressure	1,620 lbs.
Heat lost by radiation and convection	70,430 units.
Mean temperature of chimney	700° F.
„ „ air	70° F.

No combustible gas was found in the chimney.

TABLE II.—PROPERTIES of LLANGENNECH COAL.

—	Analysis of 1 lb. of Coal.	Oxygen required for Combustion. Pounds.	Products of Combustion at 32° F. Cubic Feet.	Products of Combustion at 32° F. Volume Per cent.
Carbon	0·8497	2·266	25·3	11·1
Hydrogen	0·0426	0·309	7·6	3·4
Oxygen	0·0350	..	..	..
Sulphur	0·0042	..	..	..
Nitrogen	0·0145	..	0·18	85·5
Ash	0·0540	..	..	
Total	1·0000	2·572	..	
$9\frac{1}{3}$ lbs. nitrogen	..	..	118·9	
6 lbs. excess of air	..	..	74·4	
Total cubic feet of products per 1 lb. coal	..	..	226·4	100·0

I will apply Carnot's doctrine to this case.
Potential energy of the fuel with respect to absolute zero—

	Units.
238·25 lbs. × 530° abs. × 0·238	= 30·053
194·46 lbs. × $17\frac{1}{3}$ × 530° × 0·238 the weight and heat of air	420·060
194·46 × 14,544 units heat of combustion of carbon	2,828,200
Total energy	3,278,313
Heat absorbed in evaporating 26·08 lbs. of water in fuel	− 29,888
Available energy	3,248,425

Temperature of furnace—

The whole of the fuel was heated up, but the heat absorbed in the evaporation of the water lowered the temperature of the furnace, and must be deducted from the heat of combustion.

	Units.
Heat of combustion	2,828,200
„ evaporation of 26·08 lbs. water	− 29,888
Available heat of combustion	2,798,312

Dividing by 238·25 lbs. gives the heat per 1 lb. of fuel used = 11,745 units.

composition, and the weight and volume of air required for its combustion. The total heat of combustion in lbs. of water evaporated

$$= 15 \cdot 06 \left\{ 0 \cdot 8497 + 4 \cdot 265 \left(0 \cdot 42\dot{6} - \frac{0 \cdot 035}{8} \right) \right\}$$
$$= 15 \cdot 24 \text{ lbs. of water from and at } 212^\circ$$
$$= 14{,}727 \text{ units of heat.}$$

The temperature of the furnace not having been determined, we must calculate it on the supposition, which will be justified later

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And temperature of furnace $\dfrac{11{,}745 \text{ units}}{18 \cdot 125 \text{ lbs.} \times 0 \cdot 238} + 530^\circ = 3{,}253^\circ$

Temperature of chimney $700^\circ + 460^\circ$ . . . . . . $= 1{,}160^\circ$

Maximum duty $\dfrac{3{,}253^\circ - 1{,}160^\circ}{3{,}253^\circ}$ . . . . $= 0 \cdot 643^\circ$

Work of displacing atmosphere by smoke at 700°—

	Cubic feet.
Volume of gases at 70°	= 228·3
" " 700°	= 499·8
Increase of volume	271·5

	Units.
Work done $= \dfrac{194 \cdot 46 \text{ lbs.} \times 271 \cdot 5 \text{ cub. feet} \times 144 \text{ sq. in.} \times 15 \text{ lbs.}}{772 \text{ units}}$	= 147,720
Maximum amount of work to be expected $= 3{,}248{,}425 \times 0 \cdot 643$	= 2,101,700
Deduct work of displacing atmosphere	= 147,720
Available work	1,953,980

Actual work done—

	Units.
1,620 lbs. of water raised from 60° and turned into steam at 53 lbs.	= 1,855,900
Loss by radiation and convection	70,430
10½ lbs. ashes left say at 500°	1,129
Total work actually done	1,927,459
Unaccounted for	26,521
Calculated available work	1,953,980

The unaccounted for work therefore amounts to only 1⅓ per cent. of the calculated available work.

Sir Frederick Bramwell ingeniously arranged his data in the form of a balance sheet, and showed 253,979 units unaccounted for; but if from this we deduct the work lost in displacing the air, the unaccounted for heat falls to less than 4 per cent. of the total heat of combustion. These results show how extremely accurate the observations must have been, and that the loss mainly arises from convection and radiation from the boiler.

on, that 50 per cent. more air was admitted than was theoretically necessary to supply the oxygen required for perfect combustion; this would make 18 lbs. of air per 1 lb. of coal, consequently 19 lbs. of gases would be heated by 14,727 units of heat. Hence

$$T = \frac{14,727 \text{ u.}}{19 \text{ lbs.} \times 0 \cdot 238} = 3,257^\circ$$

above the temperatures of the air, or 3777° absolute.

The temperature of the smoke t was 849° absolute; hence the maximum duty would be $\frac{3,777^\circ - 849^\circ}{3,777^\circ} = 0 \cdot 7752$.

The specific heat of coal is very nearly that of gases at constant pressure, and may, without sensible error, be taken as such. The potential energy of 1 lb. of coal, therefore, with reference to the oxygen with which it will combine, and calculated from absolute zero, is:

	Units.
19 lbs. of coal and air at the temperature of the air contained 19 lbs. × 520° × 0·238	2,350
Heat of combustion	14,727
	17,078
Deduct heat expended in displacing atmosphere 151 cubic feet	− 422
Total potential energy	16,656

Hence work to be expected from the boiler

$$= \frac{17,078 \text{ units} \times \left(\dfrac{3,777^\circ - 849^\circ}{3,777^\circ}\right) - 422 \text{ units}}{966 \text{ units}} = 13 \cdot 27 \text{ lbs.}$$

of water evaporated from and at 212°, corresponding to 12,819 units. The actual result obtained was 11·83 lbs.; hence the efficiency of this boiler was $\frac{11 \cdot 83}{13 \cdot 27} = 0 \cdot 892$.

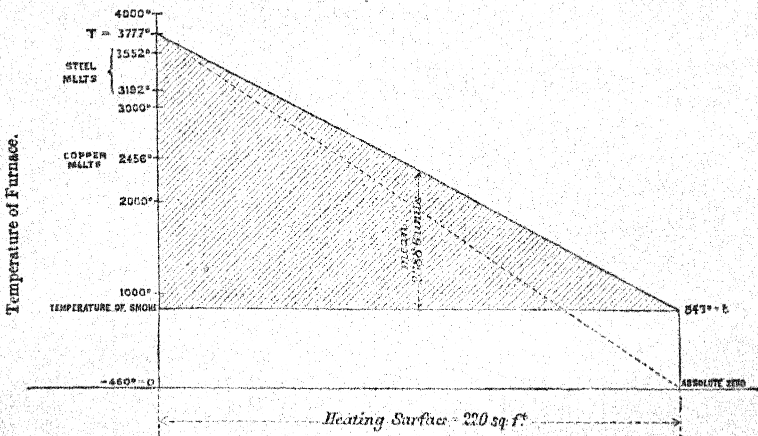
I have already claimed for a boiler that it is a veritable heat-engine, and I have ventured to construct an indicator diagram to illustrate its working.

The rate of transfer of heat from the furnace to the water in the boiler, at any given point, is someway proportional to the difference of temperature, and the quantity of heat in the gases is proportional to their temperatures.

Draw a base line representing −460° Fahrenheit, the absolute zero of temperature. At one end erect an ordinate, upon which

set off T = 3777°, the temperature of the furnace. At 849° = t, on the scale of temperature, draw a line parallel to the base, and mark on it a length proportional to the heating surface of the boiler; join T by a diagonal with the extremity of this line, and drop a perpendicular on to the zero line. The temperature of the water in the boiler being uniform, the ordinates bounded by the sloping line, and by the line t, will at any point be approximately proportional to the rate of transmission of heat, and the shaded area above t will be proportional to the quantity of heat imparted to the water. Join T by another diagonal with extremity of the heating surface on the zero line, then the larger triangle, standing

Fig. 3.



INDICATOR DIAGRAM OF BOILER OF THE PRIZE 8-H.P. PORTABLE ENGINE.

Cardiff Show, R.A.S.E., 1872.

on the zero line, will represent the whole of the heat of combustion, and the ratio of the two triangles will be as the lengths of their respective bases, that is, as $\frac{T - t}{T}$, which is the expression we have already used.

The heating surface was 220 square feet, and it was competent to transmit the energy developed by 41 lbs. of coal consumed per hour = 12,819 u. × 41 u. = 525,572 units, equal to an average of 2,389 units per square foot per hour; this value will correspond to the mean pressure in an ordinary diagram, for it is a measure of the energy with which molecular motion is transferred from the heated gases to the boiler-plate, and so to the water. The mean

rate of transmission, multiplied by the area of heating surface gives the area of the shaded portion of the figure, which is the total work which should have been done, that is to say, the work of evaporating 544 lbs. of water per hour. The actual work done, however, was only 485 lbs.

To give the speculations we have indulged in a practical turn, it will be necessary to examine in detail the terms of Carnot's formula.

Carnot laboured under great disadvantages. He adhered to the emission theory of heat; he was unacquainted with its dynamic equivalent; he did not know the reason of the difference between the specific heat of air at constant pressure and at constant volume, the idea of an absolute zero of temperature had not been broached; but the genius of the man, while it made him lament the want of knowledge which he felt must be attainable, also enabled him to penetrate the gloom by which he was surrounded, and enunciate propositions respecting the theory of heat-engines, which the knowledge we now possess enables us to admit as true. His propositions are:

1. The motive power of heat is independent of the agents employed to develop it, and its quantity is determined solely by the temperatures of the bodies between which the final transfer of caloric takes place.
2. The temperature of the agent must in the first instance be raised to the highest degree possible in order to obtain a great fall of caloric, and as a consequence a large production of motive power.
3. For the same reason the cooling of the agent must be carried to as low a degree as possible.
4. Matters must be so arranged that the passage of the elastic agent from the higher to the lower temperature must be due to an increase of volume, that is to say the cooling of the agent must be caused by its rarefaction.

This last proposition indicates the defective information which Carnot possessed. He knew that expansion of the elastic agent was accompanied by a fall of temperature, but he did not know that that fall was due to the conversion of heat into work. We should state this clause more correctly by saying that "the cooling of the agent must be caused by the external work it performs."

In accordance with these propositions, it is immaterial what the heated gases or vapours in the furnace of a boiler may be, provided

that they cool by doing external work and, in passing over the boiler surfaces, impart their heat-energy to the water.

The temperature of the furnace, it follows, must be kept as high as possible.

The process of combustion is usually complex. First, in the case of coal, close to the fire-bars complete combustion of the red-hot carbon takes place, and the heat so developed distils the volatile hydro-carbons and moisture in the upper layers of the fuel. The inflammable gases ignite on or near the surface of the fuel, if there be a sufficient supply of air, and burn with a bright flame for a considerable distance round the boiler. If the layer of fuel be thin the carbonic acid formed in the first instance passes through the fuel and mixes with the other gases. If, however, the layer of fuel be thick, and the supply of air through the bars insufficient, the carbonic acid is decomposed by the red-hot coke, and twice the volume of carbonic oxide is produced, and this, making its way through the fuel, burns with a pale blue flame on the surface, the result, as far as evolution of heat is concerned, being the same as if the intermediate decomposition of carbonic acid had not taken place. This property of coal has been taken advantage of by the late Sir W. Siemens in his gas-producer, where the supply of air is purposely limited in order that neither the hydro-carbons separated by distillation, nor the carbonic oxide formed in the thick layer of fuel, may be consumed in the producer, but remain in the form of crude gas to be utilized in his regenerative furnaces.

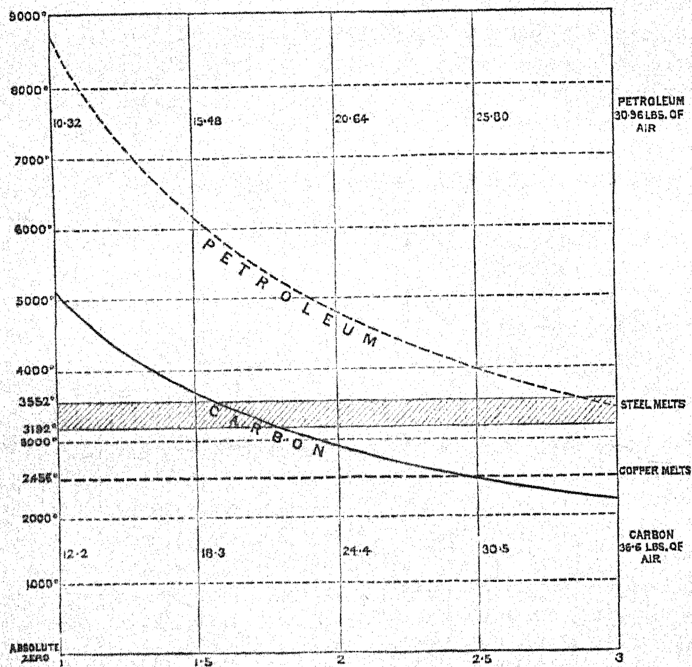
The great enemy to attaining a high temperature in the furnace is the quantity of air required to ensure perfect combustion.

We have seen that 12·2 lbs. of air are sufficient for the complete combustion of 1 lb. of carbon, which will then develop sufficient energy to raise the temperature of the products of combustion to 5150° absolute. In practice, however, a considerable excess of air has to be used, and the energy developed, which is not increased by the excess of air, is expended in heating a greater weight of gases, and consequently the temperature is lowered. Fig. 4 exhibits this effect by means of a curve, which indicates the temperature of a furnace with from 12·2 lbs. to 36·6 lbs. of air per lb. of carbon.

Unfortunately no pyrometer exists by means of which the temperature of furnaces can be readily ascertained, but the melting-points of steel have been determimed with some accuracy. The late Sir William Siemens recently told me that cast steel with 1 per

cent. of carbon melts at 3,192° absolute, whilst steel boiler-plates melt between 3,462° absolute and 3,552° absolute, and that the latter is very nearly the melting-point of platinum. On Fig. 4 I have drawn lines parallel to the base, indicating the extreme temperatures of melting steel, intersecting the curve of furnace temperature. You will observe that to melt boiler-plates the quantity of air admitted should not exceed $1\frac{1}{2}$ times the theoretical quantity,

Fig. 4.



Effect of Quantity of Air admitted to a Furnace on its Temperature.

and even for cast steel it must not exceed $1\frac{3}{4}$ times. Now it is well known that crucible steel is melted in a common coke fire with a very moderate draught, and Mr. Webb tells me that in his locomotives the temperature of the furnace is sufficiently high to melt the cast-steel fire-doors should they accidentally drop in. It is probable, therefore, that the volume of air usually admitted is not more than 18 lbs. per lb. of fuel, and I have adopted that proportion in calculating the efficiency of the Cardiff boiler. Setting

aside, for the moment, the effect of high temperatures on the materials of the boiler, it seems probable, as the late Professor Rankine has suggested, that by the use of forced blast and properly arranged furnaces, the amount of air necessary may be reduced to the theoretical quantity, and in confirmation of this view I may point to the rapidly extending use of under-grate blowers and of stoke-holes under pressure. In such cases the area of the firegrate is very much reduced, the energy of combustion, heightened almost to its maximum point, and the efficiency of the boiler greatly increased, provided that the heating surface is sufficient to absorb the additional energy developed. Unfortunately no accurate data relating to forced draught are available; I am obliged to be content with general statements, most of which tend in the directions I have indicated; indeed, until a trustworthy pyrometer is invented, the question must remain in an indefinite form.

The practical difficulty connected with raising the temperature of the furnace lies in the limited power of boiler-plates to stand the high temperature, especially with hard water. With temperatures a little above that of melting steel, there does not appear to be any trouble when the water is soft, but at higher ranges boilers wear very fast, as for example, when petroleum is used. This substance is composed of about 0·84 of carbon and 0·16 of hydrogen; 1 lb. of the oil requires 16 lbs. of air for its combustion, and yields 22,136 units of heat. The temperature of the furnace, therefore, with only sufficient air to ensure perfect combustion, is 5972° absolute, and the curve on Fig. 4 shows that to bring the temperature down to that of an ordinary furnace would require the use of twice the proper quantity of air. It is a well-known fact that the furnaces of boilers burning petroleum suffer severely, and do not last nearly so long as the furnaces of coal-burning boilers. Where this defect has been got over it has probably been by lowering the temperature by the admission of an excess of air or steam.

The temperature t of the products of combustion cannot be lowered below the temperature of the feed-water. In condensing engines this is about 100°, but without enormously extending the heating surface this point cannot be attained, and the temperature of the chimney must be kept at least 100° higher, or at 200°. In the Cardiff engine the smoke temperature was only about 65° higher than that of the steam, and suppose that by means of feed-heaters in the flue the temperature of the smoke could be reduced to 165°, then, with 18 lbs. of air to the lb. of coal, the fall of temperature from $389° - 165° = 224°$, would yield $19 \text{ lbs.} \times 224° \times 0·238$

= 1,013 units, competent to raise 11·83 lbs. of feed evaporated per lb. of coal 85·6°, or to a temperature of 185·6°, which would still be 103° short of the temperature of the boiler; hence it follows that in a well-proportioned boiler, carefully worked, the feed-water cannot be raised in temperature more than 80° or 90° by means of heaters in the flues. It is sometimes said that a feed-heater in the flue is no better than an extension of the heating surface of the boiler, but the above calculation will show that it is necessary to sever the heater from the boiler, and keep it at the lowest possible temperature so as to take advantage of the low temperature of the smoke.

In practice the chimney temperature cannot be lowered to the point indicated, unless forced draught be employed, and I believe that, independently of the advantage gained by the improved duty due to the higher temperature of the furnace, there is a positive gain if moderate blast pressure be used. In the experiments made with H.M.S. "Satellite" and "Conqueror" in 1882, it was found that $\frac{1}{4}''$ air pressure in the stoke-hole produced the same result as the ordinary chimney-draught, that $\frac{1}{2}''$ pressure corresponded to the steam blast in the chimney, and that 1" of pressure was sufficient to ensure about 38 per cent. additional steam, but at a sacrifice of efficiency on account of the boilers being forced beyond their heat-absorbing powers. Eighteen lbs. of air at 60° measures 236 cubic feet, and if forced in under an inch of water-pressure would absorb 1,224 foot-lbs. of work, or, assuming 50 per cent. duty, 2,447 indicated foot-lbs. per 1 lb. of coal consumed. An engine burning 5 lbs. of coal per I.HP. per hour would absorb 91 units of heat in doing this work, but the heat abstracted from the smoke by lowering its temperature we have seen is 1,013 u., hence the power necessary to produce forced draught is only about $\frac{1}{11}$ of that gained by cooling the smoke down to 165°. The necessity, in any case, of building chimneys to carry off the smoke has, no doubt, deterred nearly everyone from trying forced draught, not as a means of temporarily increasing the boiler-power, as is the case in torpedo-boats and the larger war ships, but as the proper and rational way of exalting the duty obtained from fuel, namely, by raising the temperature of the furnace and lowering that of the smoke to the utmost extent possible in accordance with Carnot's theory. Unfortunately the experiments which have been made by Messrs. Thornycroft, Messrs. Hawthorn and Co., and the Admiralty, were not directed to the question of economy of fuel, but to the amount of steam that could, on an emergency and at any sacrifice, be got out of a boiler. Of course the economic results were very

bad, for although the temperature of the furnace was raised to a point which, in the case of the "Satellite" and "Conqueror," made the tubes and seams leak, yet the chimney temperature was also raised even as high as 1,200°, a temperature considerably above red heat. Experiments are still wanting to show the result of exalting the heat of the furnace, while restricting the weight of fuel burned to such an extent that the heating surface of the boiler will take up all the heat developed, and part with the smoke at as little as possible above the temperature of the feed-water.

We have seen that the duty of the Cardiff boiler was 0·892. How is the loss of 0·108, say 11 per cent., to be accounted for?

In the first place, there is the obvious source of loss in radiation from the furnace to the ashpit and furnace-door, and radiation and convection from the body of the boiler. The losses under these heads can be reduced to a small matter by properly arranged ash-pits and doors, and by careful lagging.

Next, there is an indefinite loss arising from imperfect combustion. As already stated, Favre and Silbermann invariably found carbonic oxide in the products of combustion, and had to make corresponding corrections in order to obtain true results.

The other source of loss lies in the transfer of heat from the heated fuel and gases, first to the boiler-plates and then to the water. In the furnace the radiation from the incandescent fuel is very intense, and most of the heat is transferred to the boiler-plates by this agency, because very few points of the fuel are in actual contact with the plates, and therefore are not in a condition to transmit by conduction. Iron and copper are probably only slightly diathermanous, that is to say, at the thicknesses which occur in practice, a very small proportion of radiant heat passes directly through the plates. Most of the information we possess respecting diathermancy is derived from Melloni's experiments, published in 1833; but, unfortunately, such ordinary substances as iron and copper do not enter into the long list of out-of-the-way bodies he tested.

All energy transferred by undulatory movement, whether heat, light, or sound, suffers absorption or reflection in passing from one medium to another; thus, in passing through the clearest glass, a ray of light emerges, shorn of some of its brilliancy, a part being reflected, and a part absorbed. The rays of heat, in like manner, are arrested to a varying extent, depending on the nature of the substance, in part reflected, in part absorbed; and Professor Tyndall's recent experiments on fog signals at the South

Foreland show that sound is in like manner affected when passing through media of varying density.

The rate of transfer of heat through a plate varies directly as its thickness, directly as the difference of temperature on its two sides, and probably inversely as its absolute temperature; but, unfortunately, it is impossible to ascertain what the actual temperature of either side of a boiler-plate is. It is quite certain that the side of the plate next the furnace is very greatly below the temperature of the fuel and flame, because, if it were not, copper furnaces and brass tubes, which melt below 2,000°, would very soon be fused; and, on the other hand, on the water side we have no means of telling how much hotter the plate is than the water. It is evident that the greater part of the radiation from the fuel must be reflected backwards and forwards, keeping up the temperature of the gases which part with their heat-energy by degrees as they pass along the flues.

A certain amount of heat-energy passing through a boiler-plate is lost in keeping up the molecular motion of an imperfectly elastic material. It may be likened to the flow of water through a pipe inclined so as to be "in train," that is, till the rate of inclination exactly equals the retarding force of friction. The longer the pipe the greater amount of head will disappear in overcoming friction, and so the thicker the boiler-plate the greater difference there will be in the temperature of its two sides, and the greater loss of heat in the passage of a given quantity.

Again, at the surface, where the heated gases touch the plates, and where the plates touch the water, there is a change of density and of material, and consequently a certain amount of loss arises. We do not know sufficient of the nature of heat-motion to say what takes place in its transfer by conduction from one body to another; but it is certain that wherever there is a joint, even in a bar of uniform material, there a certain amount of resistance and loss arises. To illustrate this I have arranged the following experiment. A round copper bar, $\frac{3}{8}$ inch diameter and 12 inches long, is placed over a Bunsen burner, so that the flame shall heat the centre of the bar. One-half the bar is solid, the other is made up of four pieces screwed tightly together, so that there are three joints. At each end is a brass cup holding a measured quantity of water, and into each dips a thermometer. On heating the bar it will be found that the thermometer on the solid half rises more quickly than the one on the jointed portion. It is probable that even in the closest joints the contact is imperfect, and much of the heat has to pass through a thin layer of air. All

who are familiar with forging are aware that defects in metal, invisible when it is cold, will show themselves when the metal is heated by the difference of luminosity, caused by imperfect conduction through the defective portion.

At first sight it would appear to be a matter of common sense that a boiler which contained its furnace within itself must be a better generator than a boiler with an external furnace formed of brickwork; but experience does not justify such a conclusion, and there are, in fact, good reasons why it should not. The brick-lining of a furnace is an extremely bad conductor of heat. In cupolas used for melting iron I have seen a lining worn down to between 1½ inch and 2 inches thick completely protect the sheet-iron casing, even in the hottest zone; so much so, that the tar with which the iron had been coated was not sensibly affected by a temperature which must have been higher than 3,000°. Brick-lining is also a powerful absorber, and consequently radiator of heat; advantage of which property has been taken in ordinary reverberatory furnaces, in which the radiant heat emanating from the fuel is reflected down upon the hearth by a brick arch, and in many locomotive fire-boxes, where brick arches are introduced in order to intercept and mitigate the destructive heat radiated from the fuel, and yield it again in a less intense form.

The gases forming the products of combustion are very bad absorbers, and very bad radiators of heat. Pure dry air and nitrogen are absolutely incapable of absorbing or radiating heat; they are not affected in the least by the passages through them of the most intense heat-rays. Carbonic acid is a somewhat better radiator, while the vapour of water is a good absorber, and therefore a good radiator.

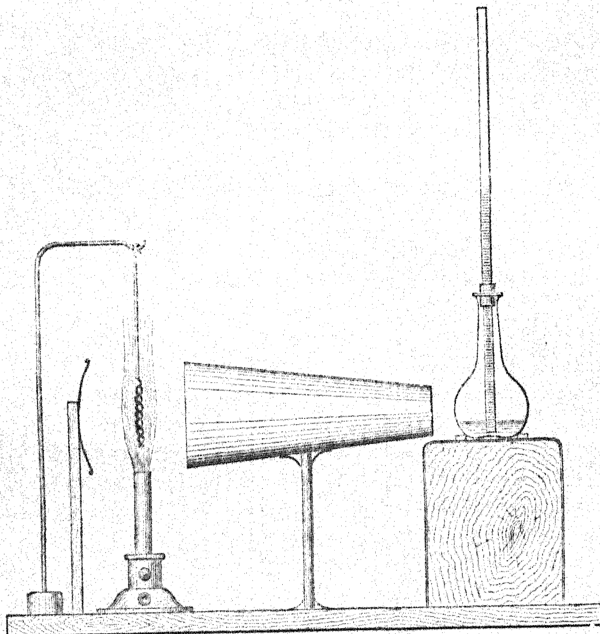
Referring to Table 2, it will be seen that the products of combustion of Llangennech coal consist of—

	Cubic Feet.	Per Cent.
Carbonic acid	25·3	11·1
Vapour of water	7·6	3·4
Air and nitrogen	193·5	85·5
	226·4	100·0

85½ per cent. of air and nitrogen, mixed with only 14½ per cent. of carbonic acid and vapour; hence the gases, taken together, must be very bad radiators. This want of radiating power, however, can be overcome by letting them heat by contact some good solid radiating substance, such as the particles of carbon forming smoke, or the soot-coated walls of brick or metal flues. It is for

this reason that the perfect combustion of flaming fuel, in an ordinary boiler, is not necessarily, or even generally, attended with economical results. The smoky products of combustion, though at a lower temperature, are much more efficient radiators, and part more readily with what heat they have than the transparent and hotter products of perfect combustion. I have arranged an experiment to illustrate this, Fig. 5.

FIG. 5.



Here is a common Bunsen burner, from which the air is shut off, and which has been burning with this luminous and comparatively cold flame since the commencement of the lecture. The radiant heat has been concentrated by means of a concave silvered mirror and polished cone on to the blackened bulb of a large air thermometer. The liquid has attained its maximum height, and has been steady there for some time. I now admit air, and produce the intensely hot but transparent Bunsen flame. You will see little or no difference in the temperature indicated by the thermometer; the colder flame is luminous because it is full of white hot particles of carbon, which are good radiators; while

the hot flame consists of air, nitrogen, carbonic acid, and vapour, which, taken together, are bad radiators. But if I hang a spiral of iron wire in the Bunsen flame, it begins to glow, and the thermometer, by its rapid rise, declares that the heat of the flame is now being powerfully radiated from it.

Now it is a notorious fact that hardly any economy results from so arranging a boiler that it shall produce no smoke, the reason being that the products, deprived of particles of carbon, become deficient in radiation, and carry the unused heat away to the chimney. If any decided advantage were obtainable by the suppression of smoke, Acts of Parliament would not have been necessary to enforce it. The truth is that a different class of boiler is required for hydro-carbon fuel, such as flaming coal and petroleum, as distinguished from carbon fuel, such as the anthracites and coke. In the first class wide flues are desirable, because combustion continues far along the flues, and the radiant powers of the smoke are high; in the latter case the products must be subdivided as much as practicable by means of small tubes, so as to bring the gases as intimately as possible into contact with the heating surfaces. But here a caution must be given as to the use of small tubes, for unless the chemical changes have taken place completely before the gases reach the tubes, there is danger that the cooling down which follows the subdivision of the gases will arrest the process of combination—put the fire out, in fact—and allow unconsumed gases either to escape altogether, or to ignite after they leave the tubes, doing no useful work. I have arranged an experiment which shows this process very fully. An ordinary Bunsen burner is made to burn with a small luminous flame. Pieces of ½-inch gas-tube, of lengths varying from 1 inch to 6 inches, are placed over it in succession. The shortest tube allows the flame to pass through; the longer ones extinguish it, but the partially consumed gases can be lighted again at the upper ends of the tubes. The action is the same as in the miner's safety-lamp, the gases are cooled below the temperature at which chemical reaction can take place. A tube, which in its cold state extinguishes the flame, if heated will permit it to burn.

I found, by means of experiments made with boiler-tubes, placed over a jet of crude gas from a Siemens' producer, that 6 feet was the maximum length which a boiler-tube of 3-inches diameter should have, if combustion were intended to go on within it. It is a matter of common observation that in marine boilers, especially those in which there is very little space between the fire-grate and the tubes, the gases are extinguished and re-light at the up-take

end, making the chimney red-hot; the glare of the flame, and even the flame itself, being often seen at night, or even against a dark cloud in the daytime.

It is manifest that any arrangement by which the gases could be stirred about in the flues would assist in depriving them of their burden of heat; this can be accomplished, to some extent, by bafflers in the flues causing eddies, or, as has been recently proposed, by giving the smoke a spiral motion as it passes up the chimney, the said motion being propagated backwards through the flues.

Owing to water being an extremely bad conductor, and almost completely adiathermanous, it is commonly held that the lower halves of tubes and internal flues are inactive in transmitting heat to the water, and no doubt this is the case, but they act powerfully in an indirect manner. The soot lodging in them absorbs, and therefore radiates, heat powerfully; the gases in contact with the soot heat it, and this heat is, by radiation, transferred to the upper halves of the tubes and flues, and so made available.

In the same way, in sectional boilers set in ovens, the gases are greatly subdivided and tormented; they heat up the sooty brickwork setting and partitions, and these transfer the heat by radiation to the boiler surfaces, suffering little to escape by conduction and radiation into outer space.

The general conclusions to be drawn from the above considerations are, that the most efficient boiler will be found to be one in which a moderate forced draught is used, the chimney being merely lofty enough to carry the smoke to a sufficient height to avoid creating a nuisance. A feed-water heater should be fitted in the flue, beyond the boiler. If the water be soft, an external furnace is admissible, but if hard, a flue furnace acts best, with a flue of large diameter. In both arrangements the boiler-plates immediately over the grate should, probably, be protected by fire-brick linings. The space between the grate and the tubes, if any are employed, should be sufficiently voluminous to admit of complete combustion, and the tubes should be used only to absorb the energy from the heated gases. In such an arrangement the conditions laid down by Carnot can be satisfied, and the highest duty obtained from the fuel. The importance of ensuring complete combustion of the gases evolved from fuel before they are brought into contact with cooling surfaces has been fully recognised by Mr. Frederick Siemens, who, in accordance with this principle, has introduced very important improvements into the regenerative

gas furnace. He has enlarged that portion of the furnace in which combustion takes place, and he so introduces the gas and air that the flame touches neither the sides or crown of the furnace nor the substance which is being heated, but acts only by radiation from its brilliant and intensely hot mass. The results of the improvement have been that the material to be acted on is not nearly so much injured or wasted as when the flame was brought into contact with it, and the brickwork of the furnace, the crucibles, &c., last much longer. Mr. Siemens proposes to introduce the same principle into boilers, and has shown that, by properly arranged rings of the flues, the flames can be kept from contact with the boiler plates and suffered to heat them only by radiation. The more complete and energetic chemical action thus obtained results in a higher initial temperature, prevents the formation of smoke, and consequently secures better economic results.

In the Indicator-Diagram, Fig. 3, I have assumed that the rate of transmission of heat from the gases to the water, is in direct proportion to the difference of temperature, but this is probably not strictly correct, because the conductivity of substances varies inversely as the temperature, probably as the absolute temperature; hence the rate of transfer of heat at the furnace end will be slower in proportion than at the chimney end, but to what extent it is impossible to say, because the mean temperature of the boiler-plates is unknown. It is certain, however, that it is below even the melting-point of lead, or 630°, because lead safety-plugs are frequently used, even in locomotives, and they do not melt out unless there be a want of water. If we assume the mean temperature of the plates at the furnace-end to be 500°, and that of the chimney-end 350°, then the rate of transmission at the cooler end will be about 18 per cent. greater than at the hotter. Were it not for the imperfect absorption of radiant heat and reduced conductivity, caused by high temperature, ebullition over and about the furnace would be so violent that uncontrollable priming would surely take place.

The rate of transmission of heat by the heating surface of a boiler can now be approximately calculated.

We have seen, in the case of the Cardiff boiler, that the combustion of 41 lbs. of coal per hour is capable of yielding 525,572 units of heat. The mean temperature of the gases was estimated at 2,313° absolute; that of the water in the boiler, 784°; hence the mean difference of temperature was 1,529°. The heating-surface being 220 square feet, U, the number of units

of heat absorbed per square foot per difference of 1° per hour would be,

$$U = \frac{525{,}572 \text{ units}}{1{,}529^\circ \times 220 \text{ sq. ft.}} = 1 \cdot 56 \text{ unit.}$$

In this case, glowing fuel and heated gases impart, chiefly by radiation and convection, their energy to water at a lower temperature. The action is the inverse of that which takes place where hot water or steam is used for heating buildings; we might expect, therefore, according to the doctrine of exchanges, that the work done per unit of surface and difference of temperature would be approximately the same.

In the 48th volume of our Proceedings will be found a curve from which the units of heat given out by a 2-inch wrought-iron hot-water pipe may be ascertained. For a difference of 190° between the temperature of the water and the air being heated, 590 units per square foot per hour were given out; this is equal to 3·1 units per square foot per difference of 1° per hour, or about double the amount realized at the Cardiff trials. This is accounted for partly by the fact that the plates and tubes of the boiler of the portable engine were, on the whole, thicker than the metal of the heating-pipes; partly by the conducting power of the surfaces having been reduced in consequence of their high temperature, but chiefly by the circumstance to which I have already alluded, namely, that the temperature of the furnace-plates, for a considerable portion of the smoke-run, is very much less than that of the glowing fuel and gases, hence the mean temperature of the plates would be considerably lower than that of the products of combustion.

Until a trustworthy pyrometer is invented, it will be impossible to determine more accurately the rate of transmission, but it may be stated that in practice 12 square feet of flue heating-surface, measuring only the half over the gases, or 10 square feet of small tube surface, measured in the same way, will transmit the heat necessary to evaporate 1 cubic foot of water per hour from and at 212°. The French allow one square metre, or 10·76 square feet per horse-power, but I am not aware that the value of a French boiler horse-power has been accurately defined.

The next point to claim our attention is the velocity of the gases through the flues and tubes of boilers.

The weight of air ordinarily necessary for the combustion of 1 lb. of coal is 18 lbs., producing, at 32° Fahrenheit, or 492° absolute, 226 cubic feet of gases. This volume, when heated up to the

temperature of the furnace, will become $\frac{226 \text{ cubic feet} \times 3{,}777^\circ}{492^\circ}$ = 1,735 cubic feet; and assuming that the gases cool uniformly along the heating-surface, then, in the case of the Cardiff boiler, where the ratio of the tube surface to the total surface was as 194·6 square feet : 220 square feet, when the gases reached the tubes in the fire-box they would have had an absolute temperature

$$= (3{,}777^\circ - 849^\circ) \times \frac{194 \cdot 6}{220} + 849 = 3{,}439^\circ,$$

and the volume $= \frac{226 \text{ cubic feet} \times 3{,}439^\circ}{3{,}777^\circ} = 1{,}579$ cubic feet.

By means of a similar calculation, the volume at the smoke-box end of the tubes, where the temperature was 849°, is found to be 390 cubic feet.

The boiler at the trials consumed 41 lbs. of coal per hour, and the area through the tubes was 1·22 square foot; hence the velocity per second at the fire-box end was $= \frac{41 \text{ lbs.} \times 1{,}579}{60' \times 60' \times 1 \cdot 22 \text{ sq. ft.}} = 14 \cdot 74$ feet per second, and at the smoke-box end 3·64 feet per second, the mean being a little more than 9 feet per second. The boiler was, however, worked to only about one-third of its power. From a number of boilers in actual work, with chimneys of moderate height, I have deduced that for a temperature of 400°, a velocity of 10·8 feet per second is admissible; this corresponds to 10 square inches of flue section per boiler horse-power (which I define to be 1 cubic foot of water, evaporated from and at 212°), and for a consumption of 1 lb. of coal to 10 lbs. of water converted into steam.

There is one source of loss in connection with the combustion of fuel which must be touched upon, and that is the heat absorbed in the work of displacing the atmosphere. The gases evolved from the fuel at the furnace end have their temperature lowered by an amount corresponding to the work performed in displacing the air, and this work is very considerable, but as the gases part with heat in passing through the boiler, they contract and the atmosphere, in falling, restores the energy absorbed in lifting it. At the chimney-end, however, if the gases leave at 400°, 396 cubic feet of smoke per pound of coal are being forced into the atmosphere, and work corresponding to 447 units per pound of coal consumed is lost, the amount forming about 3½ per cent. of the available heat of combustion.

With regard to chimneys I will only remark that, except where

it is necessary to carry smoke clear of buildings, there is nothing gained by making them more than from 50 to 80 feet high. Unless the sectional area be sufficient, at least 10 square inches per boiler horse-power, the chimney is very likely to become "in train," that is to say, the motive force gained by lengthening the hot column of gases is counterbalanced by the friction which the sides of the chimney oppose to the passage of the smoke. I have met with two or three instances of this kind; indeed in tall chimneys, with a good deal of internal taper, considerable benefit has often been derived by reducing the height. The effective area of a chimney should be measured at its smallest part.

The last consideration which will occupy our attention, is the conditions of the water and steam in the boiler.

First as to the water. Water is not only almost adiathermanous, or opaque to radiant heat, but it is also a very bad conductor; the consequence is that neither by radiation nor by conduction, can any considerable depth of liquid be heated. Advantage is taken, though I believe unconsciously, of this adiathermancy in the globes of water, used by diamond cutters to concentrate light on to their work; glass lenses cannot be used, because the spot of light in the focus of the lens would also be a spot of considerable heat, but the water lenses allow the light to pass, while they completely arrest the rays of heat. In the palace of the Grand Duke Constantine, at St. Petersburg, I have seen a very efficient fire-screen formed by a sheet of water falling from a pipe, placed in front of and above the fireplace, into a trough concealed by the fender.

The mobility of water, however, neutralizes the want of conductivity and diathermancy, and heat is distributed by convection. The molecular motion of the heated boiler-plates is communicated to the films of water in contact with them; the consequent expansion which ensues causes a diminution of specific gravity and the films rise, making room for fresh layers, which get heated in their turn. When the water has risen to a temperature, corresponding to that of steam at the particular pressure, the convective action is augmented in consequence of the molecular motion transcending the limits of aqueous cohesion, causing the water to become impregnated with steam bubbles, and its density thereby still further reduced. The body of water, however, lying below any upward heating surface, such as the upper half of flues and tubes, is not so favourably placed; the heated layers remain in contact with the plates, they cannot rise vertically, and the viscosity of water prevents any rapid sliding along inclined or curved surfaces.

The heat has to be carried downwards, partly by induced currents caused by the convection currents of the water, above the heating surfaces, gradually drawing up the water below them, and partly by heat conducted downwards by the boiler-plates from the upper heated portion of the shell of the boiler. This action, which is necessarily very slow, is especially noticeable in boilers which have no external flues, such as those of the marine type, and in these steam must be got up very gradually, so as to allow the water in the bottoms to get heated by the slow process I have described, otherwise the difference of temperature, between the top and bottom of the boilers, produces strains which are apt to end in troublesome leaks. It is very advisable, therefore, if on the score of durability alone, to set boilers in external flues, whenever possible.

Steam in contact with water, when the action is sufficiently energetic, is always more or less impregnated with particles, which are an assemblage of molecules, which have not succeeded in emancipating themselves from the bands of cohesion, but which have been carried up by the energy of those molecules which have. The molecular theory of evaporation is that the molecules of a fluid, to which the energy of heat has been imparted, perform excursions of varying extent and velocity, their motion being incessantly modified by the collisions which the molecules receive from each other. It is only to the average motion that a definite value can be ascribed, and although the average motion in fluids is much less than in gases, yet the motion of some molecules of a heated fluid may be as great and even greater than the average velocity of the molecules of a gas. Hence, if molecules near the surface of a liquid happen to have this extreme velocity, and if the movement happens to be outwards from the mass, then those molecules will escape from the fluid, and form part of the substance of the gas. Conversely the molecules of the gas, which in their excursions strike the water, have their momentum reduced to such an extent, by communicating their motions to other molecules, that they are unable again to free themselves, and they once more become parts of the liquid; they are condensed, in fact. When evaporation has ceased from the surface of a liquid, it does not mean that the action above described has ceased, but merely that a balance has been arrived at between the molecules ejected, and the molecules falling back and retained in the liquid. So soon as, by the application of heat to the liquid, or cold to the gas, the balance is destroyed, evaporation sets in with greater or less rapidity, according as the disturbance of equilibrium is more or less considerable.

When particles of water are carried up into the steam-space, their return to the water is interfered with by the viscosity of the atmosphere of steam in which they find themselves. Many solid substances, and all liquid and gaseous ones, are more or less viscous. The researches of Sir W. Thomson, of Poiseuille, Graham, O. E. Meyer, Helmholtz, Stokes and Clerk Maxwell, have determined the laws which govern this property of matter. The rate at which a particle will fall through a viscous substance is directly as the difference of density between the particle and the substance, directly as the square of its diameter, inversely as the absolute temperature and independent of pressure; hence it is obvious that the decrease in the diameter of a particle will cause a very rapid decrease in its rate of falling. It is easy to satisfy oneself of this truth, by mixing up a little ordinary mud with water. It will then be seen that the coarser particles soon fall to the bottom, the smaller ones follow gradually in the order of their linear dimensions, but there will remain a residuum of very fine particles, which take days and even weeks to settle down completely. Some waters, notably those of the Nile, are impregnated with particles so minute that they cannot be separated by filtration through sand or filter paper, nor will they subside in any definite time.

In the atmosphere, again, particles of moisture, smoke, or dust, subside in the same manner at varying rates. Professor Tyndall found, in his beautiful experiments instituted to overthrow the doctrine of spontaneous generation, that it required three days for all the dust to settle down in a box 14 inches long by 14 inches high, and $8\frac{1}{2}$ inches deep, so as to become what he called "optically empty," that is to say, that a vivid ray of light should pass through without revealing its track. When the impurities are so thick that they sensibly alter the specific gravity of the gas, then the whole mass moves together; this phenomenon may be seen in fogs and thick cold smoke, which will lie in hollows and pour down valleys like water, and present a level upper surface.

All substances, even gases, vary much in viscosity. The coefficients of hydrogen and carbonic acid are smaller than the coefficient of air, while that of oxygen is greater. It has been calculated that a drop of water $\frac{1}{1000}$ part of an inch in diameter will fall 0·8 of an inch, or 0·067 foot per second in the region of the clouds, and if the diameter of the drop be $\frac{1}{10000}$ of an inch, the rate will be $\frac{1}{100}$ of the above, or about $\frac{1}{2}$ inch per minute. As far as I know the coefficient for steam has not been determined.

It is evident that if an upward current exists in the medium

through which the foreign particles are sinking, that they will move with a velocity which will be the difference between the velocity of the current and of their own downward tendency; if the upward current is more rapid than the rate of falling the particles must be carried upwards, and will be so carried as long as the velocity of current is maintained. Now in steam boilers the proportion which the free water-surface bears to the power of the boiler varies very greatly, and the velocity with which the steam rises from the surface is not only inversely as the area of the free surface, but also inversely as the pressure, while the viscosity is unaffected by the pressure. In Table III. I

TABLE III.—PRIMING OF BOILERS.

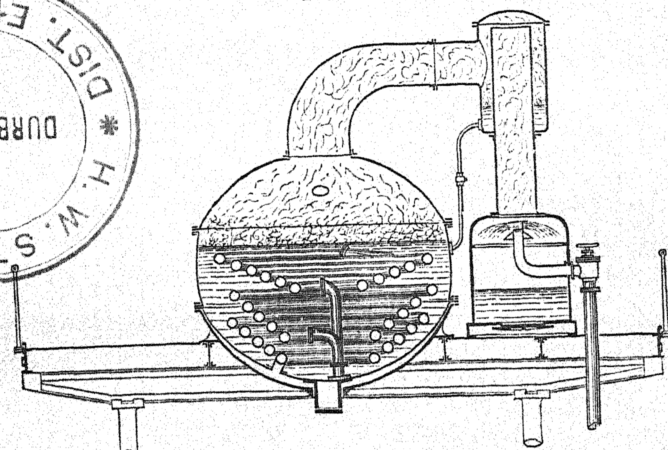
Class of Boiler.	Velocity of Smoke in Tubes 400°, 10 lbs. Water, 1 lb. Coal.	Heating Surface.	Water Surface.	Water Evaporated per Hour.	Steam Pressure.	Steam Generated per Second.	Velocity of Steam rising from Water Surface.
	Feet per sec.	Sq. Ft.	Square Feet.	Cubic Feet.	lbs.	Cubic Feet.	Feet per sec.
1. Plain two-flue Cornish, set in brick flues	..	439	139·3	36·0	50·0	4·07	0·029
2. Two-flue Cornish multi-tubular, set in brick flues	10·76	512	127·8	48·15	45·0	5·43	0·043
3. Single-flue marine	9·58	296	53·13	40·0	60·0	3·90	0·074
4. 8-HP. Cardiff portable engine as tried	4·36	123	20·51	7·794	80·0	0·615	0·030
5. 8-HP. Cardiff portable engine worked full power	13·08	123	20·51	23·38	80·0	1·845	0·090
6. Three-flue marine	10·54	852	104·8	152·0	70·0	13·34	0·127
7. Compound locomotive, L.N.W. railway	39·82	595	50·3	179·7	150·0	8·49	0·169
8. Locomotive used as stationary, overworked	35·15	664	58·54	150·0	100·0	9·92	0·169
9. Root's sectional	..	460	9·72	28·7	70·0	2·52	0·259
10. Vacuum-pan, 8 feet diameter	..	386	50·6	198·6	−13·5	1,026·0	2·66

have collected ten varieties of boilers, and have given the heating surface, water surface, rate of evaporation, steam pressure, and velocity per second with which the steam rises from the water. I have arranged them in the order of this velocity, and, bearing in mind that a drop $\frac{1}{1000}$ inch diameter falls at the rate of 0·067 per second, it will be noticed that in the plain Cornish and the two-flue Cornish multitubular boilers, the upward velocity is less than this, while in the others it is greater. The three-flue

marine boiler, in which an enormous heating-surface is packed under a very small water-surface, the velocity is 0·127 foot, and the tendency to carry up water, or to "prime," is very strong, while the stationary locomotive, with a velocity of 0·169, could with difficulty be worked at the rate of evaporation given. The Root boiler is an exceptional case, because there the steam is superheated, the evaporation, in fact, completed in the steam space.

The Vacuum pan, Fig. 6, is one of the most instructive cases. The velocity is very high, on account of the immense specific volume of the steam at 13 lbs. vacuum; the boiling is consequently very violent, and the priming is so great that "savealls," or collectors,

FIG. 6.



VACUUM PAN.

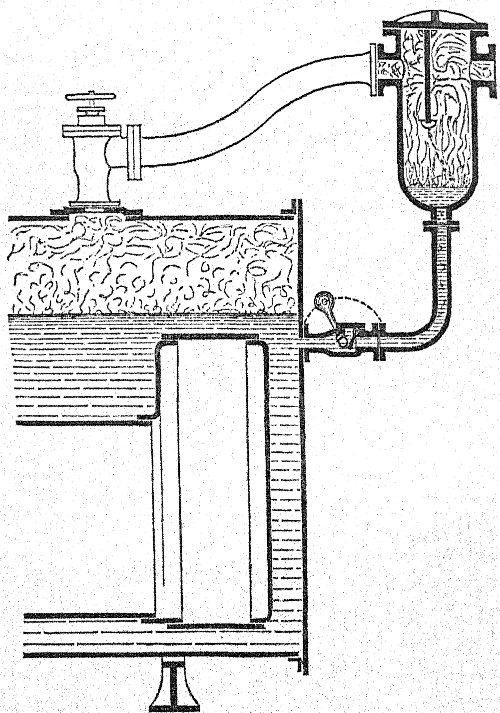
are a necessary equipment of a pan. Pans are always provided with peepholes or lunettes, by means of which it is possible to observe what is going on. Over the wild commotion of the water-surface rests an atmosphere of steam as transparent as the air; no water particle is large enough to break up or intercept the passage of the light, and yet large quantities of sugar and water accumulate in the savealls, raised by the high velocity of the steam which is 2·66 feet per second. The particles must therefore be extremely small and numerous.

The existence of solid matter in water, and in the steam derived from it, is often revealed by the accumulation of sediment in the steam chests and other steam spaces of engines. Boilers

working on the Nile, for example, show no indication of priming till the floods come down, but then the extremely fine particles of mud are carried up by the molecules of steam into the steam space, and not being able to sink faster than the steam rises, are carried over into the engines.

It follows from the thermo-dynamic theory of evaporation and viscosity which I have just laid before you, that steam-domes and

FIG. 7.



STEAM SEPARATER.

strainers cannot be of any use to check ordinary priming. The area of a steam-dome, or of a strainer, is necessarily many times smaller than the area of the free water-surface; hence the velocity of the steam passing through them must be very much greater than that of the steam rising from the water, and if, in the latter situation, it is competent to carry up particles, it is plain that they cannot be precipitated in the steam-dome or the strainer, where the velocity is higher. This fact has been found out by experience,

for steam-domes are very seldom applied nowadays to any kind of boiler, though in the case of marine boilers both steam-domes and strainers may be found useful to obviate the coarser kind of priming due to the violent motion of the vessel.

The most successful way of separating water carried along by steam is to cause the latter to impinge against a plate interposed at right angles to its course, to cause it to turn down and pass under the edge of the plate, and continue its course on the other side. (Fig. 7.) The particles of water dashed against the plate adhere to it, and, trickling down, drop off at the lower edge, but in particles too coarse to be again carried up by the steam. The water so collected is returned to the water space of the boiler.

It is evident that it is impossible to assign any numerical value to the amount of priming to be expected, since it depends, not only on the form of the boiler and the steam-pressure, but also on the quality and condition of the water, the latter, if impure, varying from day to day.

The slowness with which smoke falls to the ground, after escaping from a chimney, proves, first, that the particles of soot are very minute; and secondly, that there are not a sufficient number of them sensibly to affect the specific gravity of the gases in which they are suspended. The inference is that the waste of fuel in the form of smoke is really not very serious, and not sufficient to counterbalance the loss I have already alluded to, of radiant power in the products of combustion, caused by perfect chemical combination.

The practical deduction to be made from the statements which I have had the honour of laying before you, is that no very marked improvement is to be expected in boilers. All sorts and shapes have been tried, and the best of them do not surpass the duty obtained at Cardiff, where extreme skill in management was combined with a comparatively light demand on the powers of the boiler. When inventors come to you and propose to effect the usual saving of 50 per cent. in your fuel consumption, you will be able to fix them to something more definite, and then, if they understand the subject at all, you will find that their pretensions will be materially modified.

You will also have noticed the important part that absolute temperature plays in all thermo-dynamic problems. I trust that the day is not far distant when all thermometers will be graduated from absolute zero. It will be but realising Fahrenheit's idea, only with better information, and although it will, at first, sound strange to hear people talk, for example, of a very cold night with

the thermometer at 460°, meaning the zero of Fahrenheit; still, we shall soon get accustomed to that, and will have the advantage of abolishing negative readings and mistakes in calculations arising out of them.

I have now completed the task assigned to me by the Council, and have shown how the potential energy of fuel is converted into the potential energy of steam at high pressure and temperature. It will be the duty of my successor at this table, Mr. E. A. Cowper, on the 17th of January next, to show by what mechanical contrivances the potential energy of steam is converted into the energy of motion, suited to the wants of man. My subject is by no means exhausted, but time will not permit me to touch on the important points relating to incrustation, corrosion, and some other matters of interest.

To the late Professor Rankine, I believe, is due the honour of having first pointed out the true principles on which the duty of a boiler should be estimated, namely, by comparing the work actually done with the potential energy of the fuel used, and I cannot conclude this lecture without paying a tribute of admiration to one who was a brilliant ornament to our profession, who combined in his own person the qualities of a profound mathematician, of an acute physicist, and of an excellent practical mechanic, and whose early death has deprived the profession of a member who had done so much for its advancement, and the science of thermo-dynamics of one of its most devoted and successful votaries.

The very day on which I handed the MS. of this lecture to Mr. Forrest, one of the brightest stars in our firmament was hastening to his setting.

I had intended sending a proof to Sir William Siemens in the certain expectation that, with the kindliness and consideration which has marked every action of his life, he would have looked through my work and given me, and this Institution, the benefit of advice founded on his extensive and accurate knowledge. You must have noticed how often I have quoted his name, and the regrets I have expressed in the want of a high temperature pyrometer. In writing to me in October last about the melting-point of steel, Sir William Siemens concludes by saying: "I am now following up a plan of getting reliable indications of temperature exceeding the limits of melting steel." In addition, therefore, to the already too numerous causes of regret we must add this, that the production of a trustworthy high-temperature pyrometer has been indefinitely postponed; for I know of no man living so

competent to accomplish a task which will severely tax the most cultivated intellect, and require the command of exceptional facilities for experiment.

I spoke of Sir William Siemens as a star which had set for ever; his influence, however, will not so soon fade away. Just as this generation is profiting by the solar radiation which fell on the earth countless ages ago, so will the labours of our late colleague form a store of knowledge, potential with respect to this and succeeding generations, destined to confer advantages, greater than we can now estimate, to the ever-advancing cause of science.

On the motion of Mr. Brunlees, President, a vote of thanks was passed by acclamation to Mr. Anderson for his highly philosophical and instructive discourse.

17 January, 1884.

SIR J. W. BAZALGETTE, C.B., President, in the Chair.

"The Steam-Engine."

By EDWARD ALFRED COWPER, M. Inst. C.E.

MR. PRESIDENT AND GENTLEMEN,—I appear before you to-night in compliance with the orders of the Council, and I have much pleasure in doing so, as I must confess to a very great fondness for a good steam-engine, and although it is but a simple problem to arrange the precise manner in which a given quantity of steam, of any given pressure, shall be utilized, it is a pretty and interesting problem, which well repays any slight labour there may be connected with it.

After the two very interesting lectures on heat which we have heard in this room lately, I should not attempt, even if I were fully equal to the task, to again go over the theory of thermo-dynamics, and I am grateful to the two lecturers for clearing the ground as they have done.

I will only refer to one or two observations of Mr. Anderson's, which I consider the proper introduction to the consideration of the present subject.

Mr. Anderson observed that a boiler was a veritable power-producing machine, and I have always looked upon it as such myself, for the application of the heat to the water causes the particles, or ultimate atoms, so to separate from one another by vibration or repulsion (and I do not care which for my present purpose), that the atoms form steam, and will remain as steam so long as they are not robbed of heat.

Now, if we take a long steam-engine cylinder, and put a very small quantity of water into it, and then put the piston down upon the water, and apply heat to the whole of the cylinder, we shall find that although the piston has the pressure of the atmosphere on it, the steam, as it is created below the piston, will do the work of lifting the piston against the 15 lbs. per square inch pressure of the atmosphere, so that that is the *time* at which the power is really produced by the boiler. Then if this steam is

condensed, we may utilize the power with which the piston will descend, with the pressure of the atmosphere upon it.

In any construction of steam-engine, we have to consider how the steam is measured out and utilized, quite as much as though it were so much gas that had to be paid for and burnt to the greatest advantage.

Again, if we want the steam to behave as a gas or vapour, and do its proper duty, and expand with full force, we must treat it kindly and prevent its getting a chill, or we shall find, as you will see further on, we shall lose our good horse "Power," and find our cylinders acting as condensers to our steam before its time.

I trust to make some of these points clearer presently, but you will perhaps appreciate them quicker if you know the views I hold.

It is, I consider, truly wonderful that so early as 130 B.C. Hero, of Alexandria, should have described such an apparatus as the simple re-action engine, having two jets of steam issuing at tangents from tubular arms, inserted in a vessel that is mounted, so as to be free to rotate, the steam being supplied to it from a boiler.[1]

It is remarkable that at various times the same idea has been revived, viz., in 1590, for turning a cook's spit, in place of a dog, in which case the boiler itself carried the arms for the emission of the steam. In 1648 Bishop Williams mentions it; but in more recent times, viz., about 1831, Captain Ericson made a reaction drum, and several patents have since been taken out for variations of the same idea, amongst others Avery's engine.

In 1624, it would appear, there was the first attempt made by Solomon De Caus to raise water by the pressure of steam acting upon the surface of the water in a close vessel, the steam being raised in the same vessel, so that the water had to be heated to the temperature of the steam, due to the pressure of the head of water.

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[1] Stuart on the Steam-Engine. 1829.

For the historical part of the question the reader is recommended to consult the following works:—

"A treatise on the steam-engine, historical, practical and descriptive." By J. Farey. 4to. London, 1827.

"The steam-engine and its inventors. An historical sketch." By R. L. Galloway. 8vo. London, 1881.

"Descriptive history of the steam-engine." By R. Stuart. 8vo. London, 1831.

"The steam-engine; comprising an account of its invention and progressive improvement: with an investigation of its principles, &c." By Thomas Tredgold, with an extension by W. S. Woolhouse. London, 1838.

The next step was made by Giovanni Branca, in 1628, and consisted of a jet of high-pressure steam blowing against a light wheel, very like a water-wheel, and connected by a pinion and gearing so as to do work, and it is said that stampers for a drug mill were actually driven by it.

It should be here noticed that the immense speed with which high-pressure steam issues into the atmosphere is such that if a wheel against which it acted, revolved at half that speed, it would so act as a fan against the air as to absorb the greater part of the power, if, indeed, the steam had power to drive it so fast; and if it did not go fast, the steam would not develop its power, but would constantly blow past it. I name this fact thus early, as it is a rather common idea that if, for instance, a rotary engine, runs very fast, the steam will not leak seriously past the piston. If such were the case, the engine would not have much power; but, as a fact, the high-pressure steam would overtake any piston.

The Marquis of Worcester, in his "Century of Inventions," claims to have invented a steam-engine; but it is impossible, from his description, to ascertain what his apparatus was; probably it was somewhat similar to Savery's engine of 1698.

In 1672 one Otto Guericke describes a cylinder with a tight-fitting piston, which was exhausted by an air-pump; the piston in the cylinder was then capable of lifting a weight by the pressure of the atmosphere. This is in no sense a steam-engine, but it shows that a cylinder and piston were understood in 1672.

Sir Samuel Morland, in 1682, proposed to the French Government to raise water by the force of steam, but failed to get his plan taken up. There is no description of it extant. In 1674 he had invented a stuffing-box to a pump.

Denis Papin, a French engineer, made a model, and proposed the use of a cylinder having a small quantity of water in it, and a piston. It was to be placed over a fire, so that the steam might blow the piston up, and then, on the cylinder being removed from the fire, the steam gradually condensed, and the piston came down with the pressure of the atmosphere upon it. Papin also proposed to exhaust pipes with an air-pump, and work a second cylinder at a distance.

Before 1698 Captain Savery had erected several engines for raising water by the pressure of steam on the surface of the water in a close vessel, the steam being supplied from a boiler. Then, when the vessel was emptied, and the steam shut off, and a little cold water allowed to pour over the outside, a vacuum was soon

formed, which drew up more water from the well through the suction-valve, ready for another discharge. Two vessels were generally used to one boiler. Several of these machines were made; they had no safety-valves, and one actually burst.

This machine of 1698 has been greatly improved of late years by W. Hodgkin, who ingeniously allows a small quantity of air to pass in with the water when it enters, and this more or less perfectly lies on the surface of the water, when the steam is admitted, and thus introduces a non-conductor between the steam and cold water, thus, to some extent, hindering the condensation of the steam on entering. Another very striking point about this machine, which, as you all know, is called the "Pulsometer," is that a ball-valve is moved from side to side by the simple rush of the steam, due to sudden condensation, and thus gives the alternate action, without involving any further mechanism. A comparative experiment, made with the Pulsometer and a common direct-acting pump, showed that there was not much difference in the consumption of steam. Now one word must be said here in reference to the behaviour of steam and air when mixed, as it is of importance, as we shall see later on, in surface condensers. Supposing there is some air in the vessel, mixed with high-pressure steam, of course any such steam touching the cold water is instantly condensed, and being thus annihilated, *its place is taken by air*, so that there is, so to speak, a self-acting mode, in which the air is placed in contact with the water, and of course thus acts to hinder further condensation of steam.

In 1707, Denis Papin proposed to the Elector of Cassel to construct an engine for raising water to pass on to a water-wheel. The steam from the boiler was to act upon the surface of the water in another vessel, the same as in Savery's engine, but the vessel was cylindrical, and had a float in it on the water, and into the middle of this float an iron heater was to be placed, it being introduced through a large safety-valve at the top; this was for the purpose of keeping the steam warm, and thus counteracting the cooling effects of the cold sides of the vessel to some extent. Papin had received a drawing of Savery's, and stated that his engine was constructed on the same principle as Savery's engine, but the machine was never applied practically. He omitted the suction-pipe and the advantage of a vacuum which Savery had.

Dr. Desaguliers constructed several of Savery's engines (amongst others, one for the Emperor of Russia), and added Papin's safety-valve.

Between 1687 and the year 1702, when Dr. Hooke died, New-

comen was in correspondence with him concerning Papin's model of 1687, and Dr. Hooke says, "Could you make a speedy vacuum under your second piston your work is done." By this he meant, of course, "a speedy vacuum under the piston" in his working cylinder.

It is evident from the above that Newcomen must have been alive to the advantage to be gained by working a piston in a cylinder, and resorted to the plan of supplying the steam to it from a boiler by means of a pipe and valve (like Savery), and that he further invented the plan of cooling the cylinder by cold water applied outside it, so as to condense the steam within it, till a leak hole in a piston let in some of the water (that laid on the piston to seal it), through the piston into the cylinder, and thus condensed the steam much more quickly, and brought the piston down with the pressure of the atmosphere upon it. This in itself was a grand step in advance, as Newcomen had then a piston-rod acting with power which he could apply to certain kinds of machinery, and he forthwith attached it to the end of a large beam, turning on a centre in the middle of its length, and having the pump-rods of deep pit-pumps attached at the other end. The ends of the beam had curved segments of wood attached to them (then called "horse-heads") so that the chains that attached the piston-rod to the beam, and those that attached the pump-rod should always hang perpendicularly. There was a second smaller segment of wood attached to the beam half way between the cylinder and the centre of the beam, and a chain to it suspending a vertical wooden bar, commonly called the "plug frame," and this had pins on it to shut the steam-valve and to strike open the injection-valve for cold water when the piston had got to the top of its stroke, and other pins to open the steam-valve when the piston had got to the bottom of its stroke, so as to again fill the cylinder with steam, and let the piston go up, which it did by the weight of the pump-rods outbalancing the weight of the piston and its rod. The condensed steam and injection water that had entered the cylinder were got rid of at each stroke by a small self-acting valve at the bottom of the cylinder, that opened when there was sufficient pressure in the cylinder to blow it all out. There was a gauge-cock to the boiler, and a float in a pipe rising up out of water in the boiler, so that a column of water in this pipe balanced the pressure in the boiler; thus the level of the water in the boiler could be properly ascertained. The first large engine of this kind was erected in 1712 by Newcomen and his partner Cawley, in conjunction with Savery, with whom New-

comen had made terms, as it was supposed that the engine came to some extent within a grant that had been made by the Court to Savery.* It is said that Newcomen might have been first to have taken a patent, but that Savery had more influence at Court and was beforehand. However, Newcomen's engine was soon proved to be so much better than Savery's, that very many engines were made on his plan, and Savery's fell out of use. The model of a Newcomen engine has been kindly lent by the Council of King's College through our member, Professor Shelley.

Thus, the first real "steam-engine" was made for pumping water, and it continued to be used for fifty-seven years, up to the time of Watt's first invention, and in some cases for long after. Watt alludes to it as the common engine. I have here an engraving from the Reference Library, Birmingham, kindly lent through Mr. E. B. Marten, one of the only two engravings that are known to exist of this first engine. It is interesting to shortly consider the points in which this engine fell short of a really good engine; thus, it worked only with very low steam, in fact, so low as just enough to prevent any air entering the boiler or cylinder, and a friend of mine has seen one working with the manhole lid off, and steam coming out at the opening, the engine-man not minding whether it was on or off, and when told of its being off he simply put it on and did not bolt it down. Of course, it is evident that the engine obtained all its power in the down stroke of the piston alone; and, in fact, if there had been any considerable pressure in the cylinder, it would have blown the piston up too far, and slacked all the chains. A worse fault was that the cylinder was greatly cooled by the cold-water injection, so that it took a good deal of steam and some time to heat up the cylinder before the piston could go up again, as well as some time to cool the cylinder to get a moderately good vacuum, therefore the engine worked very slowly and took a great amount of fuel.

In 1720, Leupold, in Germany, the author of a work called "Theatrum Machinarum," constructed the first high-pressure lever-engine for working a pump at the opposite end of the lever or beam, the steam being admitted from the boiler to the cylinder by a "four-way cock," and allowed to escape as soon as it had done its work in the same way; he ascribes the sole merit of this invention to Papin. This was certainly the first high-pressure pumping-engine, and it had the great merit of being able to work as fast as the water could get in and out of the pump; there was no waiting for the cylinder to be cooled down, and the steam

inside it to be condensed before a vacuum could be obtained and a stroke made, as was the case with Newcomen's engine; it does not appear, however, that it came into use to any extent.[1]

It is a very striking fact that about the same time that Watt was making his first engine in this country for pumping, a Frenchman of the name of Cugnot was at work in France making the very first locomotive, to work, of course, with high-pressure steam; this engine is still to be seen at the Conservatoire des Arts et Métiers in Paris,[2] or rather in the old church of St. Nicolas, close by, and which is used as a repository; it has two vertical cylinders, single-acting, which are connected by a chain, and alternately pull at "pawls" on levers on the axle, which "pawls" act on ratchet wheels on the axle. This machine had but a very short active life, for when running at about 2½ miles an hour just about where the Madeleine Church now stands in Paris, on turning a corner it upset, and forthwith the machine and its inventor were put into prison; this was in 1769.

After fifty-seven years' practical working of many Newcomen engines, and after James Watt had been engaged to repair a model of a Newcomen engine in 1764, he hit upon the beautiful idea of keeping the cylinder "as hot as the steam which enters it," and, in order to do this, he condensed his steam in a separate "condenser, to be kept cold by the application of water or other cold bodies;" he does not say by "injection," but the application of cold water; and, as a matter of fact, he used surface-condensers to a considerable extent, cooled by cold water applied to their exterior surfaces, though when for large engines the surface-condenser became unwieldy, he commonly used injection. It is highly probable that he abstained from naming injection to his condenser in the specification of his patent, on account of Newcomen having used it for fifty-seven years in his cylinder.[3]

One must pause for a moment to realise what James Watt had effected by changing the place of condensation, and keeping his working cylinder hot by a steam-jacket, and proper clothing outside it. He had, in fact, obtained complete command over the action in the working cylinder and the steam inside it, in place of large quantities of steam escaping him, and becoming condensed without doing work, as was the case with Newcomen's engines; he had also obtained command over the action of the condenser,

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[1] Stuart on the Steam-Engine.

[2] Institution of Mechanical Engineers. Proceedings, 1853.

[3] Specification of Watt's patent, 1769.

and could keep it as cold as he thought advisable, so as to produce a good vacuum in the cylinder. The result, of course, was obvious, as the piston could then be worked as fast as was desirable, and with a good vacuum, instead of an imperfect one, as in Newcomen's case. There was no waiting for the cylinder to be heated and cooled for each stroke, as there was the separate boiler to produce the steam and the separate condenser to kill it.

The invention of the air-pump was also included in the same specification, for the purpose of constantly keeping the cylinder and condenser free from air, as a small quantity was always carried over with the steam from the water in the boiler, and entered, more or less, through leakages, which troubled Watt very much in his earlier experiments and engines.

It is simplest to consider this engine of the 1769 patent (as it was, in fact) as a very great improvement on Newcomen's engine, for really it was still only a single-acting pumping-engine with an open-topped cylinder, with chains from the piston-rod to one end of the beam, and chains from the pump in the pit to the other end, and, of course, working entirely with the power produced by the vacuum in the cylinder bringing the piston down with the pressure of the atmosphere upon it. Many of these pumping-engines were made to pump water from coal-pits and mines, and some for pumping water for water-wheels, as at Soho, to obtain rotative power. Then, in order to make the piston air-tight, in place of having a few inches of water on it, as with Newcomen's, he proposed to use oil or wax, &c., and actually used oil in quantity in some of his experiments with an 18-inch cylinder, and an oil-pump to pump it up again; but he complained that a good deal of oil went away with the condensing water, and he at last obtained cylinders more perfectly bored out, so that, as he said, he thought he could not get half-a-crown past the piston in the cylinder.[1]

He must, however, not be considered too much in fault for such a state of things, as there are many cylinders at the present day (more than a hundred years since Watt's time) so out of round, that a shilling, not to say a two-shilling piece, might pass a piston that would just work in a cylinder; for, in fact, a large cylinder goes considerably oval with its own weight, if bored horizontally, and then put upright for work; so that cylinders ought always to be bored as they are to be worked, and, so far as possible, the fixings should be the same.

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[1] Institution of Mechanical Engineers. Proceedings, 1883. "The inventions of Watt."

In the same original patent of Watt's, he claimed, "the use of the expansive force of steam working with or without a vacuum"; also, "a steam-wheel made like a water-wheel," and he also claimed "the expansion and contraction of steam without cooling it so much as to condense it," but he showed no means of superheating it.

One of the numerous Watt models at South Kensington shows a very perfect form of "surface condenser," having 139 long small tubes, with cold water passing up them, and the steam outside.

Twelve years later Watt proceeded to patent and construct single-acting engines that gave rotative motion, by the steam acting in one direction (as in the pumping-engine), and a heavy balance weight acting in the other direction; this was fixed on the opposite end of the beam to the cylinder, and was of course lifted by the steam. We have here a model of such an engine, kindly lent by Mr. E. B. Marten; I saw two such engines at work, many years ago, one near West Bromwich, and the other near Netherton.

Watt, in his patent of 1781, shows many ways of converting reciprocating into rotative motion, foremost of which is the "sun and planet motion," of which a few examples are still at work. Watt probably invented this plan to avoid the patent of one J. Pickard, in 1780, for the use of the crank in the steam-engine; but Watt did not hesitate to put a pin in a disk, and attach a connecting-rod to it, and he does not call it a "crank," but "point of attachment of the connecting-rod."

This production of rotative motion was a great step in advance, but the motion was not regular.

The next year, or thirteen years after the first invention of the separate condenser (which did enable quick strokes to be made), Watt made a good "double-acting engine," with a stuffing-box and cover, and steam admitted first to one end of the cylinder and then to the other, so as to produce a very good rotative power. Watt explained the expansion of steam, and drew an expansion figure in one of the drawings in his patent, showing four times expansion, and explaining many ways of equalizing the power throughout the stroke, to obtain regular motion.

Watt invented the "Indicator," and probably about this time; that on the table is a Watt indicator, an elementary model at South Kensington would seem to embrace the first idea of it. Several modern indicators will be found on the library table.

Watt described the plan of passing the piston-rod through the

bottom of the cylinder direct to the pump, as in a "Bull-engine," such as made by Bull. The model of it at South Kensington is almost identical with the engraving in the 'Life of Trevithick,' and was probably made for the purposes of an action that Watt brought against Bull.

In the same specification there is described a rotary engine with valves or pistons hinged to the revolving drums, and closing down as they pass a fixed stop; also a semi-rotary engine with a fixed stop, having the steam let in on one side, and on the other the connection to the condenser, or the atmosphere, the working piston being fixed rigidly to the shaft and reciprocating in the cylinder.[1]

The patent of 1784 puts forth the idea of a steam-carriage for common roads, and gives the size of cylinders for one to carry two persons. Watt, however, strongly objected to Murdock trying his idea of a steam-carriage, and still more strongly objected to Trevithick using one with really high-pressure steam.

Watt made the first "Counters" for steam-engines, to ascertain the work they did, and also invented the several kinds of "parallel motion" for steam-engines; he also made several other very ingenious machines, mention of which would be out of place here.

It is particularly worthy of notice, how quickly the value of steam began to be appreciated as a prime mover, after Watt had shown that quick strokes could be obtained by its sudden condensation. Hornblower, who had been one of the principal makers of pumping-engines for the Cornish district previous to the introduction of Watt's invention, designed in 1781 an ingenious arrangement of two cylinders communicating with each other, the steam from the smaller being afterwards used in the larger, and the steam from the larger passing to a "separate condenser" provided with an air-pump. This was before Watt's patent for double-action in 1782. It was a decided improvement, as it rendered possible the expansion of the steam, and the consequent economy to be carried further without giving such a great variation in strains as when all the expansion was carried out in one cylinder.

It should be noticed, that this was before Watt had put forward an indicator-diagram with four times expansion in one cylinder, and certainly Hornblower must have the credit of being the inventor of the double-cylinder pumping-engine. His first engine,

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[1] Institution of Mechanical Engineers. Proceedings, 1883.

made in 1782, was erected at Radstock, near Bristol, and had cylinders 19 inches in diameter × 6 feet stroke, and 24 inches in diameter × 8 feet stroke. No doubt the "separate condenser" and "air-pump" were infringements of Watt's patent, and he cautioned the public accordingly; the next Hornblower engine was not put up until 1790.

An extremely important event occurred in 1788, being, in fact, a step towards the adoption of steam for *navigation*; an application second only in importance, for the good of mankind, to the invention of the steam-engine itself. In this year, Mr. Patrick Miller, of Dalswinton, employed William Symington to superintend the construction of a small steam-engine for a pleasure-boat; and a second one in 1789, on the Forth and Clyde Canal, attained the respectable speed of 7 miles per hour.[1]

Symington's patents were taken out in 1787 and 1801.

In 1790, Mr. Cullen (afterwards Lord Cullen), tried to induce Boulton and Watt to connect themselves with Miller's undertaking, but they declined.

James Rumsey, in 1791, patented a plan for obtaining power from steam or water, or both combined. One plan was that of two spur-wheels, either circular or elliptical, working in a casing, the steam or water being applied above, and the condenser below.

He also describes a rotary-engine having a wheel with pistons attached to it, the steam being taken through the vertical axis, and out behind the pistons, into a circular enclosing casing having stops or valves in it, which open and shut as the pistons on the wheel pass them. This is very like Watt's rotary-engine, except that the valves in the casing open and shut instead of the valves in the wheel. This form has been reinvented some dozen times at least.

Francis Thompson, in 1792, or ten years after Watt's patent for a double-acting engine, took out a patent for a double-acting atmospheric engine; he had two cylinders, each single-acting, without stuffing-boxes, and of the same size, placed one over the other, the upper one being inverted, there being one piston-rod with separate pistons for the two cylinders. A large engine of this construction was set up near Nottingham to drive a spinning mill, the cylinders being each 40 inches in diameter by 6 feet stroke, and working at 18 strokes per minute. But few were erected.

William Bull, a Cornish engineer, who had been a stoker

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[1] R. L. Galloway on the Steam-Engine.

and engine-driver for Boulton and Watt, erected single-acting pumping-engines with an inverted cylinder directly over the pumps* in the pit, a construction mentioned in Watt's patent. This form is now known as the "Bull Engine." In 1793 Boulton and Watt instituted legal proceedings against Bull, and obtained a verdict, but subject to the opinion of the Court as to the validity of the patent, and the judges were divided. Boulton and Watt also sued Hornblower with a similar result, and it was not until 1799 that they obtained a final verdict and £40,000 for arrears of patent dues.

Edmund Cartwright, an inventor of several useful machines, designed, in 1797, a steam-engine which deserves notice. It had "metallic rings to a piston working in a cylinder," the bottom of the cylinder was always open to a "surface condenser," composed of an inner and outer cylinder standing in water; then there was a valve opening upwards in the piston, which valve opened as the piston reached the bottom of its stroke; then a steam-valve let steam on to the top of the piston when it was at the top of its stroke, and the piston thus descended with steam on the top and a vacuum below it, and on arriving near the bottom of its stroke, the valve in the piston opened, and the steam rushed out into the "surface condenser" and was condensed, and the piston then ascended by the momentum of the fly-wheel. There was an air-pump. He also mentions that the engine may be worked by ether or other volatile spirit.

William Murdock took out a patent in 1799 for improvements in the valves admitting steam to the cylinders of the double-acting Watt engine. One form shown in the specification is the "D valve," which consists of a tube of "D" form, made to slide up and down in a suitable steam case. The two ends of the "D valve" are surrounded by packing on the rounded side, so that the steam shall always be contained between them. The movement of the valve uncovers the cylinder-ports and admits steam into the cylinder, and also opens the eduction-ports and allows the steam to escape.

The eduction steam from the upper part of the cylinder passes through the "D valve" to the condenser.

Another form of valve shown in this patent is a cylindrical tube, packed at top and bottom, in the same way as the "D valve"; but instead of a sliding, or up and down motion, a circular or reciprocating motion is given to the valve. Ports cast in the valve allow of the entrance and exit of the steam, as the valve passes the ports of the cylinder.

He also describes a rotary engine consisting of spur-gearing

similar to Rumsey's, but having packing at the ends of the teeth.

Murdock was anxious to introduce steam on common roads, but it was strongly opposed by James Watt. He constructed a small model high-pressure locomotive in 1784, and this was seen drawing a model wagon round a room in his house at Redruth, Cornwall. The cylinder was $\frac{3}{4}$ inch in diameter by 2 inches stroke, and the boiler was of copper, with a flue passing obliquely through it, and was heated by a spirit-lamp.

Murdock is better known by his application of coal gas for lighting purposes at Redruth, in 1792, and at Soho works and other places after the peace of Amiens in 1802.

Among other inventions of Murdock may be mentioned his use of compressed air for an engine and lift at Soho, and for ringing the bells of his house; and his apparatus for heating buildings by a circulation of hot water in pipes from a boiler. By accident he discovered that when iron borings and sal ammoniac are mixed together, they form the excellent iron-cement now commonly used for cast-iron tanks, &c.[1]

It will now be seen that Trevithick, in Cornwall, in connection with his partner Vivian, for the first time used high-pressure steam in an engine for driving the piston; though it must be borne in mind that Savery and Papin had both used steam of some pressure for driving water up a pipe, by pressing on the surface of a body of water enclosed in a close vessel, and it has been noticed that Watt said, "I employ the expansive force of steam to press on the piston," "in the same manner as the pressure of the atmosphere is now employed in the common fire engines," though he never used high pressure, nor would allow Murdock to do so, or in any way countenance its use.

Thus Trevithick may be said to be the originator of the use of high-pressure steam in steam-engines, and a very proud position this is.

The high pressure he worked with, was, to say the least, a respectable pressure, viz., 25 lbs. to 150 lbs., according to circumstances, although he had only cast-iron boilers at first in which to raise his steam, but afterwards employed wrought-iron boilers; some, 3 feet 6 inches in diameter by 40 feet long, for 100 lbs. pressure; and "Cornish boilers," 5 feet diameter, by 18 feet long, with an internal oval flue 3 feet 4 inches by 3 feet, and one 6 feet 2 inches diameter by 22 feet long, with a 4-feet flue.

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[1] Institution of Mechanical Engineers. Proceedings, 1850.

One of his first engines was a rotative engine with beam and cylinder, 19 inches diameter by 5 feet stroke, erected at "Cook's Kitchen" in 1800; this engine had a "four-way" cock for allowing of the entrance and exit of steam to and from the cylinder, and other engines were made like it. Immediately after this Trevithick engaged in the construction of a steam-carriage, which ran some time, but received considerable damage on the hilly roads in the neighbourhood; this was called a "puffer." A horizontal bellows worked by the engine was used to urge the fire. He then constructed another, which was brought to London in 1803, and with a carriage attached, ran along the New Road; he also had a locomotive on a tramway in 1804, but as it broke the tram-plates it was taken off and used as a stationary engine. The eduction pipe of this engine discharged the steam up the chimney to improve the draught. In 1808 he had a circular railway near Euston Square, on which he had an engine that ran at the rate of 12 miles per hour, but it eventually left the rails, and was not again used.[1] My father, the late Professor Cowper, saw this engine running. Trevithick also devoted his attention to pumping-engines, and invented the "plunger-pole pump," now so much used in Cornish mines, and made many high-pressure engines, and when in partnership with Bull, made "Bull engines," in which a vacuum was obtained by injection of cold water up the eduction pipe. This last arrangement was complained of by Boulton and Watt, and damages were recovered against the makers.

Engines were put up by Trevithick in the north of England as well as in Cornwall, and one or more in London, as one boiler burst and killed four men somewhere in the neighbourhood of London. An early example of a Trevithick engine has lately been rescued from destruction by Mr. F. W. Webb, M. Inst. C.E., who will be happy to show it to any member.

A few words are here necessary in reference to the Cornish system of working pumping-engines, with high-pressure steam, very expansively, and with a vacuum below the piston; for it is evident that if the total pressure on the piston towards the end of the stroke were equal to moving the load of pump and "pump-spears" (or rods), that the pressure on the piston would be far too great for the load at the commencement of the stroke; now the practice is, to cut off the high-pressure steam so early in the stroke, that the piston will only just reach the bottom of the cylinder, the result being that the piston, "pump-spears," and

[1] Life of Trevithick, by F. Trevithick.

"plunger-poles" all move with great velocity directly the steam enters the cylinder, and then the very momentum of the moving mass enables the piston to reach the bottom of the cylinder, although by that time the pressure on the piston is much less than the load.[1]

In many Cornish mines one circumstance that much helps this mode of obtaining great expansion and consequent economy, is the fact that the pump-spears and plunger-poles weigh more than the engine can lift, and it is necessary at various places in the pit to put "balance-bobs," or beams, connected to the "pump spears," with balance weights at their tail-ends, to carry part of the weight of the "spears," so that all this extra weight adds to the inertia and momentum when working with a quick stroke as mentioned.

It does not follow that the engines shall make many strokes per minute, as they often stand a considerable time between each stroke, and the "plunger-poles" always descend quickly whilst forcing up the water in their descent. The injection is often shut off whilst the engine is standing, to prevent an unnecessary quantity of water entering the condenser. This is sometimes accomplished by a valve, or the injection is thrown in by a pump, which is an excellent mode, and might be adopted with advantage in other engines, so that the bulk of the cold water should go in at the instant the bulk of the steam entered the condenser.

A very excellent arrangement for preventing air from entering by the stuffing-box, and one which ought to be more commonly known and adopted, is the "lanthorn brass," which consists in arranging two rings of packing in contact with the piston-rod, one a little above the other, and then admitting steam between the two, so that if any leak exists it only allows a little steam to pass in instead of air, which can be condensed, and therefore does not spoil the vacuum so much as air does. Water may be used instead of steam. This again was the invention of Trevithick in 1802.

The very great attention that used to be given to the engines in Cornwall (partly in consequence of their being always reported in Lean's Reports), and the above economical mode of working expansively, very justly earned them a great reputation for some time, and, in fact, gave rise to some curious speculations about the "percussive force of steam," &c., &c., much discussed at one time in this place; however, these matters are better understood now, and double-cylinder and compound pumping-engines have

[1] Farey on the Steam-Engine.

long surpassed, in economy, the simple Cornish pumping-engine for waterworks purposes.

It was owing to one of your members, the late Mr. Thomas Wicksteed, that the first Cornish engine was put up in London, about 1847, at the East London Waterworks; but it was not quite at home in its new position, as it missed the deep pit, and enormous weight of spears and poles, with their "balance-bobs," and consequently had not nearly as much inertia and momentum to help the expansion as at a Cornish mine, and therefore could not work so expansively or economically. In fact, there was only about 12 to $12\frac{1}{2}$ lbs. in the cylinder, whilst there was some 45 lbs. in the boiler at the beginning of the stroke, yet it did its work quite well.

The late Canon Moseley, of King's College, London, invented, and made, a very elegant "indicator"[1] for taking the total power of an engine in lbs.-feet without any calculation, and applied it to the engine just named; the principle on which it was constructed was that of a small disk traversing, by the varying pressure of steam, over the face of a larger disk, which was driven by the piston of the engine, so that the revolutions of the small disk which gave the notation, depended firstly, upon *the distance* it was moved from the centre of the large disk by *the power* of the steam; and secondly, on the motion of the engine-piston with such pressure on it. Thus the power in lbs.-feet was given by a counter, the motion of which was taken from the small disk.

It operated very satisfactorily, and told a tale of the engine not making quite its full stroke every time; in fact, the engine-men almost always make rather short strokes, to keep the beam from striking the "spring beams," and, in fact, to work safely. It may be observed that, as a rule, Cornish boilers for Cornish pumping-engines are worked with very thick fires, and with slow combustion; and an experiment has been tried more than once to gain some advantage by keeping the cylinder warm by passing a flue round it, but this is very liable to throw it somewhat out of truth, and to make the piston cut, and the plan is not generally adopted.

It will be seen that in following the Cornish engine the chronological order has been departed from for a moment; but, strictly, the engine of Woolf in 1804 should be here noticed, as it was a considerable step in advance towards making an economical and steadily working engine for rotative purposes. There were two

[1] Minutes of Proceedings Inst. C.E., vol. ii. (1842), p. 102.

cylinders to one beam, the one a small one, with the shortest stroke, taking the high pressure steam, and the other a larger one with the longest stroke at the end of the beam, receiving its steam from the first, and expanding it very considerably, so that the sum of the pressure on the two pistons gave a total pressure with far less variation than when the whole work and expansion was done in one cylinder, and thus produced a more regular rotative motion, and was very economical. It must, however, be noticed that Woolf, in his first patent, was quite wrong in his expansion curve; thus he stated that 30 lbs. steam might be expanded *thirty times*, and then be at the pressure of the atmosphere, whereas it can only be expanded *three times*, or rather less, to finish at the pressure of the atmosphere. However, he does go so far as to say that some variation may be made in the proportions he gives, and that the high-pressure cylinder or "measure for the steam" may be made larger or smaller.

Several improved locomotives next appeared in rather quick succession, and although they all deserve our attention, it will be impossible to go into details beyond their general characteristics.

John Blenkinsop in 1811 invented the "rack rail," either forming one of the rails or as a central rail, and a piece of an actual rail is now on the table, lent by the Council of the Institution of Mechanical Engineers, and although not at all fitted for high speeds, it is a question even now if it is not as good, as a central rack for very steep inclines and low speeds, as some at least of the schemes for the same purpose.

Two double-acting cylinders were now first applied to a locomotive, and this of itself was a great practical step in advance, and gave a great impulse to steam locomotion; the engines began to run in 1812, and ran for many years.

In 1813 three locomotives by different makers were set to work on colliery railways—viz., Chapman's chain-engine at "Heaton Colliery" (soon abandoned), one of Blenkinsop's on the "Kenton and Coxlodge Railway," and Hedley's first engine with smooth wheels at "Wylam Colliery;" the latter had a cast-iron boiler and a single cylinder and a fly-wheel; it did not steam well, and another was made with a wrought-iron boiler and "return fire tube," but still with a single cylinder and fly-wheel. This engine worked well, and drew eight loaded coal wagons at four or five miles per hour.

The continued use of this and similar engines at "Wylam Colliery" proved the highly important fact that smooth wheels could have sufficient adhesion given to them by the weight on them.

"Puffing Billy," now in the Patent Office Museum at South Kensington, started in 1813 or 1814; it had two cylinders, and ran for many years.

George Stephenson at this time was "chief engine-wright" at Killingworth, two or three miles from the Kenton and Coxlodge, Heaton, and Wylam Railways, and in 1814 constructed a locomotive with a wrought-iron boiler and wrought-iron internal tube passing *through* it; two vertical cylinders 8 inches diameter and 2-feet stroke, let into the boiler, with cross-head and connecting-rods outside the boiler; it was thus similar to Blenkinsop's of 1811, but it had smooth wheels, like Hedley's. It worked for some years.

Ralph Dodds and George Stephenson patented, in 1815, the arrangement of attaching the connecting-rods directly to crank-pins in the wheels, and thus the spur-gearing previously used was abandoned, the two axles having double cranks and connecting-rods between the bearings to couple the axles.

Stephenson applied springs in 1816 to locomotives, and thus gradually did the locomotive acquire the character of a practically useful machine.

The locomotives on the Stockton and Darlington railway (which was the first line to carry passengers regularly) were not altogether satisfactory, and no high speed could be attained; but Timothy Hackworth, who was manager of the working department of the railway, put inverted cylinders to a locomotive, placing them on each side of the boiler, and connecting them at right angles to the same axle; this was another step in the right direction, due to direct action, although the vertical position of the cylinder was objectionable on account of the power of the engine setting the springs in action.

Hackworth used the "return fire-tube" in his boiler, like Trevithick and Hedley had done, in place of the straight tube that Blenkinsop and Stephenson had used, and he narrowed the orifice of the eduction pipe in the chimney, so as to make a better "blast-pipe" of it, and thus to urge combustion in the fire most materially.

The use of this "blast of exhaust steam" was not unknown to Trevithick, but Nicholas Wood said "it was laid aside, or only partially used when only slow rates of speed were required."

The time was now fast approaching for the opening of the Liverpool and Manchester railway, and it had not been settled how it was to be worked, and a prize was offered for the best means. It will be seen how the efficiency of the locomotive had gradually been increased, partly by simplifying the parts, but

very much by improving the evaporating power of the boiler, first by a "return fire-tube," and then by a forced draught.

The competing engines were the "Sans-pareil" of Hackworth, made as above described; the "Rocket," by Stephenson, and the "Novelty," by Braithwaite and Ericsson.[1]

The most striking improvement in the "Rocket," which gained the prize, was that of having the "multitubular boiler," the idea of which, it is believed, was first suggested by Mr. Booth, then secretary to the railway; the tubes were 3 inches diameter, and twenty-four in number, and a square fire-box surrounded by water, and attached to the boiler containing the small tubes, supplied the heat that passed through the tubes to the chimney, the draught being urged (at all events after the few first trials) as in Hackworth's engine, by a "blast-pipe," but the second great alteration was that of putting the direct-acting cylinder at an inclination to the axle, in place of their being vertical, and later on they were put still nearer to a horizontal line than at first, so as to avoid acting on the springs and making the engine jump, as the "Sans-pareil" did, and as the "Manchester" afterwards did.

The "Rocket" had 8-inch cylinders; 1 foot 6 inches stroke, and a boiler 3 feet diameter by 6 feet long.

This engine drew $9\frac{1}{2}$ tons, weighed, with water and coke, $3\frac{1}{5}$ tons, and ran at 12 miles per hour.

The "Novelty," by Braithwaite and Ericsson, had a very economical boiler—in fact too economical for full useful effect; it had a round fire-box surrounded by water, and the body of the boiler was a long cylinder, with one long flue, of small size, of copper, passing backwards and forwards the whole length several times, and the fire was forced through this flue by a pair of bellows, worked by the engine. It was a very light engine, and would not draw a heavy load, and the flue gave way several times, but I think it is only due to the memory of my old master, John Braithwaite, to state that it was the first engine that ever ran really fast, as it did a mile in fifty-six seconds.

There is no doubt whatever but that the new construction of boiler employed in the "Rocket" gave the grand impetus to locomotion; and this, together with other improvements in the engine and mode of working the slide by the link motion, has given us the ordinary locomotive of the present day.

It has been necessary, in order to connect in one's mind the

[1] "A Practical Treatise on Railroads and Interior Communication in general." By Nicholas Wood. London, 1831 (and various later editions).

progressive steps in the improvement of the locomotive, to leave behind for the moment the progress of steam navigation; but since the early experiments on Dalswinton Lake by Symington, in 1788, and on the Forth of Clyde canal in 1802, and Mr. Cullen's attempt to get Boulton and Watt to help Miller in his attempts, Fulton, in America, had built a boat called the "Cleremont," in 1807, which ran as a regular passenger-boat between New York and Albany, the engines for which were made at Soho, by Boulton and Watt; this was so successful that it led to the building of larger steamers in America.

In the year 1812, Henry Bell, in Scotland, started a boat about 40 feet long and 4 HP., to carry passengers between Glasgow and Greenock; this was soon followed by the boats on the Clyde; and in 1817 the "Caledonia" was the first steamboat to cross the Channel from England to the Continent, running from Margate to Holland.

Other boats were now built and began to run regularly; one, the "Rapid," was seen by the late Professor Cowper somewhere about this time.

The Henry Maudslay, in 1807, made a very neat form of condensing engine for land purposes, without a beam, of a form often called a "table," or "pedestal engine," the cylinder standing on a "stool," or "table," and having a cross-head and side-rods to a crank-shaft below, which had a central short-throw crank to work two short levers or beams, for working the air-pump and cold-water pump. There are engines of this construction still working.[1]

Very many attempts at improvement, and some real improvements, follow about this time in quick succession, and time does not admit of a full description being given of them, but a few words must be said in reference to several.

In the year 1822, Jacob Perkins appears to have commenced his experiments, and made a high-pressure boiler that, it was intended, should be full of water; and in 1827 had another with small tubes with water in them, and a steam-chamber for high-pressure steam. In 1831 he had vertical tubes projecting down from the boiler and closed at the bottom, but with circulators inside them in the form of smaller tubes, open at top and bottom, so that the water could flow down the inside tube, and the steam and heated water could flow up the space between the two tubes. The internal tube or

[1] "An Historical and Descriptive Account of the Steam-Engine." By C. F. Partington. 8vo. London, 1822.

circulator had not a trumpet mouth at the top to throw the uprising steam away from the current of water flowing down the centre, as the "Field tubes" of the present day have.

Thomas Howard had an engine he called a "Vapour Engine," but later on he had a more practical form of the same thing.

Walter Hancock in 1827 made an ingeniously-constructed boiler which was of great interest, as he succeeded in accomplishing a great deal of work with it, in steam-carriages on common roads, having regularly run some four or five along the New Road from Paddington to Finsbury Square, for many months together, and having run longer trips to Brighton and elsewhere; and I well remember following one called the "Experiment" some distance from Brixton towards Croydon. The boiler consisted of a number of flat chambers with water in them, placed near together, but allowing room for the fire to play up between them, the whole being tied together, outside, with tie-rods and light girders, and the flat chambers taking a bearing against each other, at places where they were bulged out for the purpose. Hancock drove the wheel-axle by means of a horizontal chain from the crank-shaft, and thus allowed the springs full play.[1]

Samuel Hall, in 1831, showed a mode of attaching the numerous small tubes of a condenser, like Watt's surface condenser, to the end tube-plates by means of stuffing-boxes, a plan much used at the present day.

In 1832 Trevithick proposed to propel a boat by ejecting water from the stern.

Thomas Howard had a further improvement in his "Vapour Engine," by which he obtained a chamber in which to maintain a supply of vapour from the water injected on to a plate on the surface of a liquid amalgam of mercury and lead, the intention being to evaporate the water very quickly; and he said the water might be heated beforehand.

Samuel Hall further improved his "Surface Condenser," and applied distilling apparatus to keep up the supply of fresh water when at sea.

Ernest Woolf patented the idea of coupling two or more distinct engines, one to take steam from the boiler, and the second to take the exhaust steam from the first.

Francis Humphrys (brother of the late Edward Humphrys, M. Inst. C.E., of Deptford) brought out an ingenious form of engine in 1835, intended chiefly for paddle-wheel steamers; it had

[1] Hancock's specification of Patent No. 5514 of 1827.

a hollow piston-rod, in the form of a flat trunk, to allow of the vibration of the connecting-rod inside it, the lower end of the rod being joined to the piston. A pair of engines on this plan were put on board of a steamer called the "Dartford," which lay in the East India Docks for a long time. This boat had Hall's Surface Condenser.[1]

In the same year Spiller's boiler came out, with a large square firebox surrounded with water, and with a large number of small tubes, full of water, and crossing the inside of the box from side to side, the tubes being at an inclination of about 3 inches to a foot, so as to give quick circulation. Some fair results were obtained from a few small boilers in boats, but there was not much done with it on a large scale.

Again in the same year William Symington introduced a highly ingenious plan for condensing the steam, or cooling the fresh condensing water, in pipes outside the ship, laid along on either side of the keel; but this proved to be too exposed a situation.

W. Taylor and H. Davies patented a disk-engine in 1836, which was a special form of rotary engine, having a chamber of the general form of a central slice cut from a sphere, which had two ends of a conical form projecting towards the actual centre, with teeth like two bevel-wheels, but they did not quite reach the centre; then, attached to a large central solid ball, there was a disk with teeth on it, fitting the teeth on the cones, and gearing into them when such disk was inclined, and this inclination was obtained by means of an arm firmly fixed in the central ball, and having the other end inserted in a small fly-wheel at a distance from its axis, so as to form in fact a crank-pin. The disk had a slit in it, to enable it to roll round on the cones, and pass a division fixed at one point between the cones.

The steam was admitted continuously on one side of the fixed division, and escaped on the other side. The teeth on the disk and cones were intended to prevent the steam passing the two lines of contact of the cones and disk, and the steam continually pressing on the disk, caused the arm to move round, and so turn the fly-wheel.

The leakage of steam was so serious that it was often impossible to tell, by looking at the eduction-pipe, whether the engine was at work or not. This engine was strongly backed up by a company for a time, but it is believed that there is not one at work at the present time.

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[1] Tredgold on the Steam-Engine.

Several inventors attempted to improve it, amongst others Mr. Bishop, who has a very ingenious but complicated plan of making it expand the steam somewhat.

In the year 1839, Elijah Galloway proposed a highly ingenious arrangement by which two cylinders could drive a crank continually, owing to their being connected to the two upper ends of a frame like the letter T, and the bottom being connected to the crank, the effect on the shaft being the same as though the two cylinders were at right angles one with the other.

A variation of Davies's disk-engine is described in the same patent, having a disk, without teeth, to vibrate in the barrel, which is part of a sphere, the disk being jointed in the centre and the barrel revolving.

Thomas Craddock, in 1840, designed a "Surface Condenser," to be put in motion in air or water. It consisted of a large number of small vertical tubes, inserted in tubular arms, into which the steam from the engine entered through a central stuffing-box. This condenser when working in the open air gave a very fair vacuum, even on a hot day in August.

The boiler was composed of a large number of vertical, or nearly vertical, tubes connected at the top and bottom by chambers, and surrounding the fire, which was at the bottom. This boiler would carry 90 lbs. steam with great safety, but had no large quantity of water in it to keep the steam regular. He some time after put a high-pressure cylinder to give its steam to a low-pressure cylinder, the cranks being on the same shaft.

David Napier built some boat-engines on the Thames about 1842, with four light vertical piston-rods to one cross-head above the paddle-shaft, the connecting-rod descending from the cross-head to the crank in the paddle-shaft, and the rod and crank working between the piston-rods. The same effect may be obtained by two piston-rods, as is now commonly done in many horizontal marine engines for screws. It appears that such "Return Connecting-rod" was quite new at the time Napier introduced it.[1]

I well remember as a lad being sorely puzzled to see any good reason why steam should not be used first at a high pressure, and then be expanded and condensed in all situations where condensation could be managed. Later on, in 1844, after I had made a number of simple high-pressure engines, I had an opportunity of making a pair of 35-HP. engines, and I drew out an expansion curve from Pambour's table of the pressures and relative volumes

[1] "The Artizan," 1854.

of steam, and at once used 50 lbs. steam, and expanded nine times, and condensed with injection, obtaining a good vacuum (with a new injection-valve), and realised great economy. I had wished to see what could be done with a pair of single-cylinder engines; but the result was not thoroughly satisfactory, so far as the regularity of motion was concerned. The expansion had to be reduced, and with the variable cut-off fitted to the engines, they were generally worked with three to four times expansion only; but the power obtained was $2\frac{3}{4}$ times that before produced from the same old boilers.

John Penn, William Hartree, and John Mathew brought out an improvement in trunk-engines in 1845, by extending the cylindrical trunk through both ends of the cylinder, and so obtaining efficient guidance for the piston.[1]

David Napier proposed to make part of a ship's bottom double, and use it as a "Surface-condenser." This, at first sight, would appear to be a good idea, but the practical circumstances of expansion and contraction, leaks, and the pumping up of the condensement, and other considerations, render such a use of the bottom of the ship very objectionable, notwithstanding the tempting fact of there being always a sharp current of the coldest water obtainable, in contact with the condenser, without the need of any "Circulating pump."

I must now very shortly notice a number of different forms or constructions of engines, some for paddles and some for screws,—thus, some time before 1846—

Messrs. Penn had introduced vertical vibrating engines both in small and large boats, and later on, Messrs. James Watt and Co. had introduced horizontal vibrating engines for screws.[2]

David Napier had a forked connecting-rod, reaching outside of a forked crosshead, for paddles.[3]

Messrs. Rennie had upright direct-acting engines for paddles, there being a parallel motion to the piston-rod.

Messrs. Maudslay Sons and Field had two cylinders, with one T-shaped crosshead, and a connecting-rod from the bottom of it to the crank of paddle-shaft.

About 1857 I determined to adopt, in common with others, a large and small cylinder, but I added a steam-jacketed reservoir

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1 "A Treatise on the Steam-Engine in its application to Mines, Mills, Steam-Navigation, and Railways." By John Bourne. 4to. London, 1846.

2 "The Artizan," 1854.

3 "A Treatise on the Steam-Engine." By J. Scott Russell. 8vo. London, 1841.

(now commonly called "Cowper's Hot-Pot") between the cylinders, and put the cranks at right angles to obtain uniform motion.

A pair of 60-HP. engines so fitted did good duty, and worked very economically; and a further improvement for obtaining a very uniform rotative power consisted in cutting off the steam at, or about, half-stroke, in both cylinders.

In numerous cases, such "compound engines," with both cylinders well steam-jacketed at top, bottom, and sides, and with the reservoir, or "hot-pot," also well steam-jacketed, are at work, giving a HP. per hour with less than 2 lbs. of good coal.

Some time before 1854, Captain Carlsund, in Sweden, had two inclined cylinders, pointing down to one crank on the screw-shaft.

Messrs. Thomson had vertical inverted direct-acting screw-engines, the cylinders resting on standards that were sometimes made into condensers, the air-pump being driven by a lever.

The "Princeton" engine, as designed by Captain Ericsson, had pistons moving about 90° in the segment of a circle, each piston being attached to a shaft which had an arm outside, taking one end of a connecting-rod which reached to the crank. The angle formed by the two connecting rods being about 90° they took hold of one crank.[1]

The old-fashioned "side-lever" marine engines were probably first made by James Watt, and afterwards by many firms; this form was exclusively used for driving paddle-wheels, and in the first ships which crossed the Atlantic.[2]

In 1862 a further improvement was made in the steam-jacketed reservoir, which consisted in not heating up the steam when it entered, but heating it up when it was drawn off from the "pot" into the low-pressure cylinder; this was accomplished in the following manner, without any valves, viz., by fixing a "lining" closed at one end and open at the other, inside the reservoir, and causing the eduction steam from the high-pressure cylinder to enter the "lining" at the open end, and making it issue from the reservoir at the opposite end from the outside of the "lining," so that the steam was obliged to pass between the "lining" and the hot steam-jacketed sides of the reservoir in a thin sheet or stream, whereby it became somewhat further warmed up, as it supplied the low-pressure cylinder, so that it might give a very much better indicator figure in such cylinder, and thus develop more power.[3]

Thus no excessive temperature was imparted to the steam, and

[1] "The Artizan," 1854.
[2] Transactions of the Naval Architects, 1864.
[3] Tredgold on the Steam-Engine.

no cutting of slide-valves or pistons occurred, as has often been the case when a high degree of superheating in the first instance has been adopted.

Perhaps the commonest form of marine engine for driving a screw propeller in a passenger and merchant ship is the inverted cylinder class, or "Steam-Hammer Engine," as it is sometimes called; the frames on which the cylinders rest being generally utilized as condensers, or surface-condensers. For the Navy, where it is necessary to keep the engines below the water line on account of shot, horizontal engines are generally adopted, and the commonest form is with two piston rods from each piston, running past the crank-shaft, and then joined with a cross-head running in guides, and with a connecting-rod returning to the crank.[1]

The cylinders of both these classes are now generally arranged on the compound principle, viz., with the steam passing from the small high-pressure cylinder to the large low-pressure cylinder, through a reservoir.

Another arrangement (often called "Tandem") of high- and low-pressure cylinders, viz., one above the other, with pistons on the same piston-rod, or practically so, is chiefly used in the merchant service; a pair being used, with the cranks at right angles.[2]

Another arrangement, chiefly adopted for very powerful engines, consists of three cylinders, one high-pressure and two large low-pressure cylinders, with an intermediate reservoir, and the three cranks at 120° apart. In some cases the crank-shaft has been built up of a number of separate pieces well fitted together.[1]

In a Paper by Mr. Holt, in 1877, he described his use of a large single-cylinder engine, with one crank only, in a large ship, there being a fly-wheel 12 feet diameter, and of 7 tons weight, to help the engine over the centres; he had adopted this form in several ships of his own.[2]

More recently Mr. Holt has adopted two cylinders, the high-pressure above the low-pressure, with one crank only, in his own ships.[1]

Mr. Kirk has adopted yet another form of engine, with three cylinders and three cranks at 120°; the cylinders are of three different sizes and very high-pressure steam, viz., about 125 lbs. enters the smallest cylinder first, and then passes through a reservoir to the next sized cylinder, and, finally, to the largest cylinder, through a reservoir, by which means great expansion is obtained.

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[1] Institution of Mechanical Engineers. Proceedings, 1881.

[2] Minutes of Proceedings Inst. C.E., vol. l. 1.

In certain cases the consumption has been as low as 1·28 lb. of coal per indicated HP., being the lowest ever recorded.

It should be noticed that at various times there had been attempts made to run steam-carriages on common roads, besides the successful working of Walter Hancock's steam-carriages, and many persons wished to push them forward in place of promoting railways.

The names most connected with these attempts were those of Goldsworthy Gurney, Colonel Maceroni, Dance, Burstall, and Hill, Church, and Gibbs.

Thomas Aveling, later on, made excellent traction-engines for low speeds, chiefly for agricultural purposes, and which are now largely used, as well as those produced by other makers.

Steam-hammers, by Nasmyth and many other makers, have been largely introduced, as well as steam-riveting machines, blowing engines, cranes, crabs, steering apparatus, air-compressing machines, cold-air machines, well-boring machines, dredgers, excavators, and steam-navvies, &c., &c.

Locomotive engines are so constantly before the eyes of everyone that it would be wasting time to attempt to describe the varieties that exist, their very names would almost fill a page; even the types are numerous, as, for instance, passenger engines and goods engines, inside and outside cylinders, coupled or uncoupled, six- or eight-wheeled, bogy, tank engines, &c., &c.

A photograph of "No. 1," the early Darlington engine, is to be seen in the library.

But one new form must be noticed, viz., Mr. Webb's three-cylinder compound engine, working with 150 lbs. steam, in two small outside cylinders working to cranks at right angles on to one axle, the steam being expanded, and then passing to the large cylinder working on to one crank on another axle, and without any coupling rods, the saving in fuel being very considerable. This engine has Joy's valve motion, which is an admirable employment of the side motion of the connecting rod, and the end motion of the piston. There are some hundreds of locomotives now building on this plan, and tens of thousands of HP. in marine engines.[1]

An excellent form of quick-working engine for torpedo-boats, and for other purposes where high speed is required, has been brought out by Mr. Brotherhood; it consists of three cylinders

[1] Institution of Mechanical Engineers. Proceedings, 1883.

arranged in a circle at 120° apart, the connecting-rods being jointed to the pistons and to one crank; the pistons are single-acting, the steam being let on to the backs of the pistons, and then allowed to escape.

As already mentioned, the early pumping engines were either beam-engines, such as Newcomen's, Watt's, and the Cornish, or the "Bull" Cornish. In more recent times, besides the two last-named, other forms have been used, as, for instance, the rotative beam-engine, either "Single," "Woolf," or "Compound," as made by Messrs. Simpson and Co. and others, and the horizontal, either direct-acting or with bell cranks, without a fly-wheel for vertical pumps in pits or wells, the last being introduced by Messrs. Hathorn and Davey, with their compound differential gear for working the valves.

To suit a special case there has lately been made an arrangement of horizontal rotative compound pumping-engine, with all parts made light for carriage 600 miles up country by bullock wagons; the pumps being double-acting and in line with the cylinders, and each engine being capable of working entirely independent of its fellow, if necessary.

Boilers.

I must only give a few words to the subject of boilers, as time will not admit of more.

In 1756 Brindley, when erecting one of Newcomen's engines at Newcastle-under-Lyme, made his boiler of brick and stone, firmly cemented together, the water being heated by iron flues passing in various directions. Other boilers were made with granite bottoms and lead tops, covered with masonry, and an uncle of mine, when an apprentice, worked at a wooden boiler made by the late Mr. Lloyd, of Gravel Lane, for a dredger on the Thames. This boiler had an iron flue, and clay was laid on the top of the boiler, to help to keep it down.

Among the earliest boilers used for the Newcomen and Watt pumping engines were the "Haystack Boilers," with a round top, and generally with a slightly hollow bottom, and sometimes with curved sides, and made of wrought iron, a large fire being placed below the boiler, and a flue circulating more or less around its sides.[1]

These boilers would carry 2 or 3 lbs. pressure per square inch, but often, when corroded at the bottom, would tumble over out of

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[1] Farey on the Steam-Engine.

their seatings, or blow up. On the table before you is a piece of a copper haystack boiler, which I replaced with a double-flued Cornish boiler. I believe this was the last left in London.

Watt's form of boiler was the wagon boiler, at first with vertical sides, but afterwards with curved sides, strengthened by cross-stays, the bottom being curved up like a flat arch; these often had an internal flue as well. Occasionally the flat ends were stayed, to prevent them from straining or "panting," as they often did at every stroke of the engine, when it was attempted to make them carry more than 3 or 4 lbs. per square inch. The continued use of this form of boiler greatly hindered the introduction of high-pressure steam.

By degrees, however, the "Double-flued Cornish Boiler," or "Lancashire Boiler," as it is often called, got into use, and then, of course, a higher pressure of steam was adopted, and in many cotton-mills an extra small high-pressure cylinder was added to a beam-engine, near the crank, on the system advocated by McNaught, and with a largely resulting economy.

Some "Egg-ended Boilers" were used from very early times, and are still used at some ironworks where the water is bad; but the ordinary "Cornish Boiler," with one flue through it, or the "Double-flued Cornish" mentioned above, have long been the standard or most usual stationary boilers, and when properly proportioned and well made, are excellent steam-makers, though they are improved by a few Galloway tubes introduced into the flues.

Marine boilers have generally stood in a class by themselves, as they cannot be set in brickwork on board ship, and therefore must have the whole of their flues complete within themselves up to the funnel.

Early marine boilers were little more than square boxes, often with curved tops, and were, in fact, nicknamed "Bandboxes," and they would carry but little pressure, though stayed in various directions; the furnaces and flues were plain rectangular boxes, giving room for a man to pass up, and, although stayed to some extent, were very weak.[1]

Lamb's boilers had a series of very narrow and deep flues, to return over the furnaces, and gave extra surface, but were difficult to keep in order, and were very weak.

One form of "Bandbox-boiler" was tried with two sets of flues one above the other, but this was soon abandoned for the far superior construction of small "return tubes" over the furnaces,

[1] Institution of Mechanical Engineers. Proceedings, 1872.

there being an uptake behind the end of the furnace, to take the products of combustion up to the tubes which were inserted in the back tube plate, and a similar box and flue in front of the front tube plate to lead to the funnel.[1]

The small iron boats above bridge were first fitted with small tubes to their boilers; and then the boat called "Father Thames" in 1840 by John Penn and Son, was fitted with small tubes passing straight through from the furnace.

The pressure now began to be raised, until during the last 20 years the shells of such boilers have more and more been made of a cylindrical form, so as to have great strength of their own, and not to depend upon stays to hold them together. Cylindrical furnaces were also adopted, and where two furnaces were not enough three were used, the middle one being at a slightly lower level for stoking, than the other two—a slight inconvenience which is well worth putting up with for the advantages obtained.[2]

Such marine boilers are now commonly working at 60 lbs. and 80 lbs. per square inch, and a few examples at 125 lbs.

I have mentioned that the late Mr. Jacob Perkins at one time used a boiler composed of tubes to supply very high-pressure steam for working a steam-gun, and a small engine that drove an iron disk at the Adelaide Gallery, when it was first erected, and our member, Mr. Loftus Perkins, has more successfully constructed boilers with small tubes for working engines at 500 lbs. per square inch. Such pressures can be controlled, and it is more a question of expediency, and the consideration of a number of practical circumstances, that must always settle the question of whether it is advisable to carry a fairly high pressure or a very high pressure. I have myself worked a boiler at 1200 lbs. per square inch for some hours together, with one man, in a building away from any others, but it was a small boiler only, and we kept a feed of water and palm oil through it, as it was for the purpose of taking the glycerine out of the palm oil, and so making acid grease. Occasionally the pressure ran to 1300 lbs.; but, as a fact, 220 lbs., and four hours' time, is amply sufficient to change palm oil into acid grease, on the plan known as Tighlman's, and I therefore erected several boilers to work at this pressure.

I ought to mention that with these high pressures, and consequent high temperatures, it is always advisable to have several little cups (formed by drilling holes a little way in) with alloys in them

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[1] Institution of Mechanical Engineers. Proceedings, 1872.
[2] *Ibid.* 1881.

melting at different temperatures, so as to know how the pressure is rising by a second means, as well as having a pressure-gauge.

I cannot refrain here from alluding to a large horizontal pulp boiler that I inspected, both before and after it had blown its cover off, as it appeared that the pressure being about up to the usual limit of 150 lbs. per square inch, one of the small wrought-iron heating-tubes inside the boiler, gave way, and so let into the boiler a charge of water and steam at perhaps 400 or 500 lbs. per square inch; and so the boiler, being quite full of liquid, it for the moment produced sufficient pressure to blow the end off, and the result was most violent; for the boiler shot ahead like a huge Congreve rocket, and first knocked down a wall of 3 feet of masonry, and ran along a very considerable distance, say about 100 feet, then cut a tree 10 inches in diameter in half, knocked down a wooden stable, and buried its front end 3 feet into a bank, by doing which, it burst the front end in. In fact, it behaved in a large way just as this tiny boiler before you did, when I blew it up, just to show my youngest son the evil of a boiler having no safety-valve.

I have seen a Cornish boiler with its flue badly collapsed, from the water having got low and the plates hot, and yet not a crack in the Low-Moor plates, though they were crumpled like leather. It must be borne in mind that the old very low-pressure boilers had their troubles also, and although they would often work the engine well enough with the manhole lid off, of course at atmospheric pressure, they were liable to collapse altogether if the pressure were allowed to run down, and they were not provided with vacuum valves; some have actually collapsed whilst working engines that were very lightly loaded. A common tin cannister, with a table-spoonful of water in it, made to boil well and expel the air, and then thrown into a cold bath, will utterly collapse in an instant.

I trust I may here be allowed to express an opinion, that a boiler should always be provided with at least two ways of showing the level of the water in it. I prefer three ways, viz., glass gauge, three gauge cocks, and a float stone; it should have a pressure-gauge, two safety-valves of good size, a vacuum-valve, to prevent its filling itself with water through the check-valve and pump-valves when the steam is let down. Two blow-off cocks, *i.e.*, one below, to blow out heavy dirt, and the other a scum-cock, to blow off light dirt that floats; a copper feed-pipe, some feet in length, placed horizontally a little above the top of the flue, but below the water-line, and with some slits in it, with the metal

bent inwards, so as to deflect water out from the pipe ; in this way the feed, if cold, does not cool and contract individual plates, or lines of plates. Very many boilers have been made to leak from cold feed being supplied at the bottom, so that the bottom has been cold when there was 20 lbs. of steam at the top, but this has occurred principally when getting up steam from cold water. In order to obviate this, every boiler, if alongside of another, should have a small steam-pipe leading from the top of one to the bottom of the other, and *vice versâ*, so that if steam was up in one, and the other cold boiler was to be heated, it should be heated from the bottom, by steam blown down into it from the other boiler; this often saves repairs. Every boiler should have its own steam-valve, independently of the engine, a damper, and the means of adjusting the quantity of air admitted over the fire, and in Cornish boilers there should be several Galloway tubes; the first should not be too near the bridge, but, say, 3 feet from the end of the bars, to prevent any chance of its burning. Every set of boilers should have an injector.

A simple means of stopping a considerable proportion of the water that may exist in steam as priming, which indeed would always take some water out of the steam, (as it is present in small quantities in all natural steam that has not been superheated,) consists of a series of inclined gridirons made of wires to intercept the particles of water as the steam rushes past. Some experiments, conducted by the late Sir William Siemens and myself, proved that the first increase in temperature of isolated steam caused a much greater expansion than the same increase in temperature above the first; in fact, that the line of expansion of isolated steam by increase of temperature is a curve to begin with, and that it then runs practically straight, just as the line representing the expansion of common air and most gases does. It is, I think, now pretty well proved that all vapours or gases expand quicker just above their liquid points, and no doubt from their still containing minute particles of the liquid.

A very good form of feed-water heater has been designed by Mr. Strong to eliminate impurities. The water, admitted at the bottom of the cylindrical vessel, is first heated by the exhaust steam from a high-pressure engine, which circulates through the vertical pipes projecting upwards into the vessel. Above is a coil of pipe supplied with live steam direct from the boiler, by which means the water is still further heated. Finally, the water passes through a filter at the top of the vessel, which abstracts from it all solid and insoluble matter, such as carbonate of lime

and sulphate of lime, which are held in solution in cold or warm water, but are deposited in a solid form at 250° to 290°.[1]

A small quantity of astringent matter (such as Arney's composition) put into the boiler prevents the carbonate of lime from crystallizing and forming hard scale, as it is precipitated in an amorphous condition (well known to chemists), and can be washed out of the boiler as mud. Many other forms of feed-water heaters have been made and used, such as Green's, which is placed in the flue and has scrapers outside the pipes to scrape off soot.

Several mechanical stokers are in use now, and answer their purpose very well, thus enabling very small coal to be used in London, at very little more than half the cost of large coal, and they keep the steam very regular. A model of one by Messrs. Vicars will be found in the library.

Boilers should be proved at 210° with water to twice their working pressure; and at such pressure the strain on the metal should be well within the elastic limit.

It may perhaps be interesting to refer to six-weeks trials of a compound or sectional boiler, made in pieces for carriage 600 miles up country, and of such construction as to avoid the use of a brickwork setting. The construction, is, in fact, that of a Cornish boiler in two sections, one containing the furnace, and the other a flue and Galloway tubes, with the addition of a third section containing a set of locomotive tubes. The results of the experiments are given in Fig. 1, and my son has set out the several curves which give the different results; perhaps the most interesting one is that which proves that, whether the boiler was evaporating 500 lbs. of water per hour, or 1,300 lbs., the economy was nearly the same; in fact, unless the boiler was very much over-driven, or was worked far too slowly, it steamed well.

The figures on the base line show the total quantity of water evaporated per hour in cubic feet from 60°. The figures below the line show the pounds of water.

The line A A shows the economy, or water evaporated per lb. of coal.

The dotted line B B shows the same, but with a larger grate.

The dotted line C C the same, with a smaller grate.

The three top lines of figures show the pounds of coal burnt per hour per square foot of grate, in the several experiments.

The line D D shows the temperature in the chimney, which was always low, viz., a little above or below 400°.

[1] Institution of Mechanical Engineers. Proceedings, 1881.

The line *a a* shows the actual consumption of coal per hour; the dotted line *b b* shows the same with a larger grate; and the dotted line *c c* shows the same with a smaller grate.

The line E E shows the square feet of heating surface per cubic foot of water evaporated per hour.

I believe it to be useful to carry out a few such experiments occasionally, as at all events, if our ideas are right, the experiments confirm them, and if wrong, we are set right. In this case it was wished to have boilers that would work very steadily at 80 lbs., and therefore a form giving a good large "pond" of water was selected; the whole was enclosed in a light corrugated iron case, filled with ashes from the boilers themselves. There were good circulation pipes between the sections, both above and below, as well as a steam-dome on the middle section, and steam-pipes from the end sections to it.

A number of these boilers were made to suit the special circumstances just named, but commonly where a large amount of steam is wanted it is best to put down large "double-flued Cornish," or "Lancashire boilers," with Galloway tubes and a brick setting, if there is room for it.

Condensation.

The subject of the condensation of the steam for producing a vacuum is so important a one, that a few words must be said in reference to the different modes of accomplishing it.

We have seen that Newcomen at first applied cold water outside his steam cylinder, to condense the steam within it; then he used an injection of cold water into the cylinder, which was of course slightly better.

Then Watt used a separate condenser, and cooled it by water applied outside it, and afterwards used injection of cold water into the condenser, thereby producing a good vacuum very quickly without cooling his cylinder.

Now, it is on the amount of cold water, or surface exposed, that the rate of condensation depends, and I know of a case where two revolutions a minute more, were obtained by simply putting a plate into the condenser for the water to splash against.

As injection pipes are sometimes arranged with valves or cocks at a distance from the condenser, the pressure, and consequent velocity of the water, is to a great extent destroyed, so that as it issues from the rose, or perforated pipe used in the condenser, it drops in large drops or streams to the bottom of the condenser.

Now, if the injection-valve is placed *in* the condenser, so that the full pressure of the water shall be exerted at the small opening of the valve, the water will issue in a powerful stream, and dash itself against the sides of the condenser, so as to be broken up into very fine spray; this gives a quicker vacuum and a better vacuum-line, in the indicator figure, whilst the condensement comes away more nearly at the temperature corresponding to the pressure, owing to less injection water having been used, and, as a necessary consequence, rather less air introduced.

A convenient form and position for an injection-valve is that of an adjustable conical valve, standing up an inch or two in the bottom of a condenser, as the conical jet of water strikes with great force against the sides and top of the condenser, thus making the whole into fine spray.

Watt also proposed a very perfect form of surface-condenser, and one that is now very largely used; it is not shown in any of his patents, but there is a good model of it at the South Kensington Museum, which has not until lately been taken much notice of; the diagram on the wall shows it very well. There are a large number, viz., one hundred and thirty-nine small vertical tubes with the cold water in them, and if they were taken as representing $\frac{3}{4}$-inch diameter they would be 5 feet long, which is a very fair proportion, they are soldered into the tube-plates at top and bottom, and the steam is admitted to the outsides of the tubes enclosed in the condenser.

The quantity of water required for such a condenser is nearly the same as for a jet condenser, viz., twenty-five to twenty-eight times as much as the water in the steam to be condensed.

It is a fact worthy of note that when any quantity of air is present with the steam in a surface-condenser, the steam as it is condensed leaves the air in close contact with the cold surface of the condenser, and thus hinders its quick action in condensing more steam. Thus the reason that a quick vacuum is attained, when a good vacuum is being produced, is that there is but little air present to hinder the condensation.

The surface of metal kept cool by the cold water is always partially covered with minute bubbles of air that are separated from the cold water by the heat of the metal exposed to the steam to be condensed; these bubbles increase in size until they come off the metal.

Modern surface condensers frequently have the tubes secured in stuffing-boxes as proposed by S. Hall in 1831.

Another form of condenser is the "surface evaporative con-

denser," with which the quantity of water required for condensation is no more than the water in the steam to be condensed; this statement no doubt appears at first sight rather startling, as we know that there is nearly six times as much heat in the steam as would bring as much water up to the boiling-point. The explanation is, that a large surface, viz., about 36 square feet of tubes, being exposed in the open air with the steam inside them, they are just kept wet with water trickling over their exterior surfaces, and the atmospheric air passing over and amongst the tubes absorbs or carries away such water in the form of steam or damp air, and the tubes being at about 120° or 130° temperature, enables a good vacuum to be kept in the engine, whilst it is enough to cause the evaporation of the water from the outsides of the tubes.

Surface evaporative condensers have for long been used in connection with sugar vacuum-pans (the weak syrup being used on the outside, and becoming strengthened by the evaporation of water from it).

Of late years a few such condensers have been put up by myself and others, and I have also put up cheap cast-iron condensers with 4-inch pipes, and wrought-iron condensers with $\frac{3}{4}$-inch tubes, which answer very well, and enable an engine of the most economical construction to be put up wherever there is a third as much water to be had as would do for a common high-pressure engine.

Another form of the same kind of condenser has been introduced by Mr. H. Cochrane, and consists of two large cast-iron pipes, one put within the other, water being applied to both, and the steam being between them.

The use of surface-condensers to supply boilers entirely with distilled fresh water created an unlooked-for evil, inasmuch as from using the same water over and over again any neutral grease that went into the cylinders got gradually converted into acid grease, from the water taking away the glycerine, and the acid grease attacked the boilers badly. This delayed the adoption of surface-condensers for a time, but by working the boilers with salt water, or with fresh water containing the usual amount of lime and magnesia, &c., this evil was cured, as the lime combined with the greases, and the whole contents of the boiler were gradually changed by moderate blowing-off. If a boiler were used continuously with the same distilled water, no oil or grease could be put to the piston or piston-rod.

Morton's ejector-condenser is worked with a good supply of cold water, and ejects the air and water from the condenser into the

open air, and condenses the steam at the same time, thus requiring no air-pump.

It will have been seen that from the time of the first practical steam-engine there were two very different schools of engineers at work, the one from absolute necessity using high-pressure steam for locomotives (and be it observed, gradually increasing that pressure up to the Trevithick pressure of 150 lbs. in locomotives), and the other school working at first entirely with low-pressure steam, and getting the power by means of a vacuum obtained by condensation. In fact they may be said to have been separated by the Atmospheric line.

No doubt the use of low-pressure in condensing engines, both on land and afloat, was continued longer than it otherwise would have been, because from the great success of Boulton and Watt, it was thought that the wagon boiler was the right form for a boiler, (though it would not carry any pressure), and because it was considered extremely dangerous to use high-pressure on board ship.

Meanwhile high-pressure steam was being used advantageously, and economically in small land-engines, where there was no good supply of cold water, and in Cornish pumping-engines in which expansion and condensation were also used, resulting in great economy.

I should not be doing justice to the genius of Watt if I did not briefly mention a statement of his, in which he claims cooling an isolated body of steam without condensing it; he omits, however, any statement as to the high degree to which it would have to be heated first to prevent condensation. Of course this is the crude idea of a caloric engine, but Watt never carried it into practice. A good steam-engine, however, may be allowed to obtain extra power by the expansion of isolated steam by heat, so far as it can be done practically by steam-jacketing.

Now, the steam-engine has practical limits of economy, at all events in our present state of knowledge, and I will not here attempt to speculate beyond.

Firstly, the boiler has its limits of economy, as it is not a perfect power-producer, as explained by Mr. Anderson; that is to say, we can, with the best boiler, only evaporate a certain quantity of water; and a knowledge of the theoretical amount of carbon and the consequent theoretical amount of heat, does not, unfortunately, teach us how to make the best boiler, as that is in fact only arrived at by experiment and practice, there being so very many circumstances to be taken into account.

Secondly, the power we can get out of natural steam has very

decided limits also, and now we must refer to the practical knowledge of the expansion-curve produced by expanding steam.

The curve on the black board is drawn on the figures given by Pambour, derived from experiments by the French Academy, and has since been very closely confirmed by the experiments of Sir William Fairbairn. (Fig. 2.)

Now, as to the limits: first, with regard to the bottom of the figure, we cannot afford to keep a condenser cold with ice, and to obtain rapidity of action in condensation, we must have our cooling medium below the temperature of the condensed steam, as is well known to all steam-engine engineers (and as referred to by Professor Reynolds).

Now, supposing it is not worth while to go below 100° Fahrenheit (and it is not, unless the condensing water is very cold) we at once have 1 lb. pressure in the condenser, and if we allow three-quarters of a pound only for air in the condenser, brought over with the steam from the boiler, we have $1\frac{3}{4}$ lb. pressure in the condenser at once, and an engine must be very air-tight, and have a very good air-pump, to keep the pressure in the cylinder down to 2 lbs. I therefore at once draw a limit at the 2-lb. line, and adopt that as the practical bottom limit, which is seldom exceeded.

I now come to the limit at the top of the figure, and here I know I am treading on what many consider debateable ground, but I trust you will excuse me if I appear to do so with too much confidence, but having been used to high-pressure as long as I can remember, I have not the least fear about the use of high steam; though I am not one to blindly adopt any one pressure, either low or high, without considering all the circumstances involved, including the boiler, that most important part of a steam-engine, and one that often gives more trouble than any other part (just as in the human body, the stomach often requires more attention than the limbs).

The boiler generally needs repairs, and wears out first, in any case, and it is therefore false economy, to unnecessarily wear out a boiler in an unreasonably short time, or to make it necessary to apply the material of which it is composed in a disadvantageous manner.

Taking therefore all points into consideration, such as very thick plates for boilers to stand very high pressures (which plates do not conduce to good riveting), I venture to state my own opinion, that at the present time, 150 lbs. or a little more, is enough for locomotives, and 80 lbs. for land and marine engines. I do not mean to say, but that with improved means of applying

hydraulic riveting-machines to every rivet in a boiler, and some alteration in design, these limits will not be passed.

We now have an area bounded by the back line (representing the cylinder bottom from which we start), the top and bottom lines, and the true expansion-curve, and the problem of making an economical engine is, to obtain as much of this area as we can without sacrificing uniformity of motion in the engine, or working a piston at a pressure so little in excess of that required to overcome friction, as to really develop no useful power, and without requiring an exorbitant amount of cold water for condensing purposes. Having assumed our top line, we have the limits within which we must practically work.

If the means we take to obtain as much of this area as possible also give us, in some part of the process, something beyond the natural expansion curve, by slight superheating, we are so far the gainers.

This area in height represents lbs., and in length it represents the feet that the piston moves; therefore the area of any indicator figure represents the lbs.-feet, or comparative HP. obtained by such use of steam.

Now, in order to appreciate the advantages and disadvantages of the various modes in which steam has been worked, I beg your attention to a few indicator figures, taken from numerous examples in my possession. As indicator figures, drawn to different horizontal scales, cannot be conveniently compared, I have drawn them all to the same scale as the true expansion curve, so that they may be compared with it and with each other. First I will take such a figure as a Newcomen pumping-engine must have produced if an indicator had been applied to it (Fig. 3). There must have been a bad vacuum, owing to the cylinder being warm, and the pressure of steam must have been a very little, if at all, above the atmosphere, and there being no idea of expansion, we have the boundaries of the figure, but not the limit of the steam used, because a good deal was condensed in heating up the cylinder, after the latter had been cooled by the injection water thrown into it; we must therefore add a considerable area to represent such condensed steam. It is, therefore, of course highly uneconomical, as much more than a cylinderful of steam is used to produce a stroke.

The first improvement upon this was James Watt's single-acting open-topped-cylinder pumping-engine, with the cylinder steam-jacketed, so that there was no loss of steam from condensation in the cylinder, the condensation being carried out in a

separate condenser, somewhat removed from the cylinder; the consequence was, that only about one-third as much steam was used to do the same work (Fig. 4). At a later period, as we have seen, James Watt made a further improvement by adopting expansion, as shown in Fig. 5.

The next, Fig. 6, is an entirely different one, and there being no condensation at all, the whole of it is above the atmospheric line; this represents Trevithick's cylinder, with his high-pressure steam; by means of the true expansion-curve we can at once compare them.

At the present day it is wonderful to us, that Watt did not adopt high pressure and expand the steam and then condense it, since he understood expansion; but this he left for Trevithick to accomplish, and, later on, Woolf.

It would have been a grand thing for the scientific and practical application of the steam-engine if Watt and Trevithick could have joined hands, and worked harmoniously together, in place of remaining in antagonism.

It would be amusing, if it were not really sad, to think that Watt actually put a covenant in the lease of his house, Heathfield Hall, now occupied by Mr. George Tangye, that no steam-carriage should on any pretence be allowed to approach the house; but such was the fact, and he discouraged Murdock, so as to prevent his being practically the father of steam-locomotion in this country, and left it to Trevithick to take that proud position.

Fig. 7 is a high-pressure figure with expansion, and it will at once be seen that it would be impossible to expand further without the pressure running down below the atmosphere, and thus making a partial vacuum against the engine. The area contained within the figure is clearly much larger than if the same steam were used without expansion, as the area would be limited to the point of cut-off.

Fig. 8 is a figure with high-pressure steam, and there being a nearly perfect vacuum below the piston, the expansion may be carried out as far as desired, and accordingly we have an area *three and a half times* as great as could be got with high-pressure steam without expansion. There would be one fault, however, amongst others, in the use of this figure, viz., the very great difference of pressure at the beginning and end of the stroke; the cure for this will be seen in other figures.

Fig. 9 is a bad one, from a winding-engine at a colliery. You will observe that not only is the steam not used to the best

advantage, but there is a loop formed which represents the retarding force due to the valve not being properly geared; but it should be noted that this figure was taken when the "skip" was going down, and therefore the engine running light.

Fig. 10 is taken from a high-pressure engine at a paper-mill; the eduction steam was being delivered to the steam drying-cylinder of the paper-making machine, and hence the extreme back-pressure shown; but the passages of the cylinder must have been too small, or the throttle-valve have been partly closed, as the steam has been wire-drawn whilst the piston was at full speed, in the middle of the stroke, and then, when the piston was going slower towards the end of the stroke, the flow of steam has overtaken the piston and filled up the cylinder with steam of full pressure, without doing any work.

This is only one of the cases, out of a very large number where steam is required; for boiling liquids, for a steam brewery, for heating buildings, &c., &c., in which the power, if also required, may be obtained at next to nothing in point of cost by using the steam first in a high-pressure engine, and afterwards for heating.

Fig. 11 is a high-pressure expansion figure from a compound engine with steam-jacketed reservoir, with the lining already described inside it. You will observe that the expansion-curve follows the true expansion-curve very well at the beginning, and is rather above it towards the end of the expansion, due to the steam-jacketing of the cylinder covers and sides.

Fig. 12 is the corresponding figure from the low-pressure cylinder of the same engine, which receives its steam from the reservoir; this runs considerably above the true expansion-curve due to steam-jacketing. The vacuum here appears low, but the engine is between 3,000 and 4,000 feet above the sea-level, which accounts for several inches of vacuum.

Fig. 13 shows a great fault in the engine, as the steam has been leaking in, to a large extent, the whole time, so that even after the steam ought to have been thoroughly cut off, it has continued to flow in, and the line has run away far above the true expansion curve.

Fig. 14 shows a good high-pressure engine working very expansively; the curve follows the true expansion curve for some time after the cut-off, and until the temperature of the steam is lower than the steam-jacket, when the line runs somewhat above the true curve.

Fig. 15 from H.M. steamship "Briton," with compound engines

and steam-jacketed reservoir, with a lining inside; the covers of the cylinders are steam-jacketed, as well as the sides. These engines gave a very economical result, viz., 1·3 lb. of coal per HP. per hour, when the ship was going at a 10-knot speed; on the measured mile at $13\frac{1}{4}$ knots, the consumption was 1·98 lb. of coal per HP. per hour.

Fig. 16 shows indicator figures by Mr. Kirk, from a compound engine having three cylinders, or triple expansion; with 125 lbs. steam, the consumption, on a four hours' trial, has been as low as 1·28 lb. per HP. per hour, or $\frac{1}{3}$ oz. under the consumption of the "Briton."

Fig. 17 is taken from a pair of pumping-engines on the compound principle, with a reservoir and fly-wheel, at the Lambeth Waterworks, working of course slower than the above, with a result of 1·6 lb. of coal per HP. per hour.

The indicator-figure best suited for steady pumping is one having rather more power than the load at the commencement of the stroke, and rather less than the load at the end of the stroke; both cylinders of the compound engine can be arranged to give this, as the expansion in each cylinder is moderate.

Fig. 18 is from a Woolf beam-engine, with large and small cylinders, at the Lambeth Waterworks.

Fig. 19 shows a pair of figures from one of Mr. Webb's compound locomotives, running at 50 miles per hour.

A little experiment, which I made many years ago, gave a very palpable demonstration of the action of the steam in a cylinder which is not jacketed. A glass tube, closed at the outer end, was fixed to a cylinder, so as to form part of it. At the commencement of each stroke the incoming steam condensed upon the interior surface of the glass tube, forming a dew or film of moisture, visible from the outside, which remained throughout the first part of the stroke; during the latter part of the stroke, when the steam had been cut off and was expanding, and consequently falling in temperature, the dew disappeared by re-evaporation. The glass was then heated from the outside by means of a shovelful of hot coals, and as long as the external heat was maintained no condensation took place.

Thus the walls of an unjacketed cylinder, being at an intermediate temperature between that of the incoming steam and that of the exhaust, condense a portion of the steam whilst the latter is at its full pressure, sacrificing the power which should have been given by the steam so condensed; and when the re-evaporation from the surface takes place, through the natural reduction of

temperature of the expanding steam *below* that of the walls, the piston is approaching the end of its stroke.

In the case of a jacketed cylinder, not only is radiation from the outer surface of the walls prevented, but heat is continually supplied, at the full steam temperature, to the outer surface, to be conveyed by conduction through the metal to the inner surface. The walls thus heated from the outside can cause no condensation of the incoming steam; and whilst the steam is expanding its pressure is kept up somewhat above the natural curve by the slight super-heating and drying action of the hot walls.

Fig. 20 shows a pair of figures from a Woolf beam rotative pumping-engine at the Lambeth Waterworks, during a trial conducted by Mr. John Taylor, M. Inst. C.E.; the cylinders were steam-jacketed, and the steam main thoroughly drained.

Fig. 21 shows a pair of figures from the same engines, on another trial, when the jackets were shut off, and the steam main not thoroughly drained. The I.HP. shown in the two cases is almost identical, and the initial pressure of steam nearly the same; but the great loss, arising chiefly from the want of steam jackets, is shown by the smaller rate of expansion in the second case, viz., 9·3, as compared with 15·76 times.

In a very able Paper, printed in a recent volume of the Minutes of this Institution, Mr. J. G. Mair, M. Inst. C.E., has published a series of tables, containing the result of elaborate and careful calculations from the data obtained from ten different engine-trials, including the two cases under consideration, and comparing the performance of the several engines in thermal units per I.HP. per hour; he calculates the consumption of coal represented in the two cases to be 1·76 lb. with the jackets, and 2·66 lbs. without. He has also kindly furnished me with some figures showing a comparison of the measurements of water from jacket drains in several trials, from which it appears that the greater the quantity of steam used in the jackets the less is the total quantity of steam and coal used to produce a given effect.

This is a distinct proof that steam-jackets are of great use; indeed, if the cylinder is not kept up to the temperature of the steam that enters it, a large quantity is immediately condensed, and its useful effect utterly lost.

Mr. Rennie, M. Inst. C.E., informs me that the result in consumption of coal, in trials extending over two periods of four weeks each, with and without steam in the jackets, of a 40-HP. stationary engine, amounted to 31 per cent. in favour of jackets.

Fig. 22 is an indicator figure taken from an air-pump.

Fig. 23 from a condenser; the stroke being taken from the piston.

Figs. 24 and 25 show the rotative power of two cylinders having their cranks at right angles, the dotted line showing their power when full steam is used, and the full lines the power when cutting off the steam at about half stroke, as in Fig. 25, and it will at once be seen that the hollow curves due to the expansion fit remarkably well to the rounded curves due to full steam; so that the sum of the two results in an almost uniform rotative power being applied to the shaft. Precisely this effect is obtained from a compound engine having the cylinders and reservoir properly proportioned, and this whilst expanding some eight or nine times.

It is of course impossible in a single lecture like the present to go into a great variety of details of construction, although many of them affect the economy, as well as the efficient working of an engine, such as the thorough supply of steam to the jacket, and drainage of water and air therefrom, the efficient protection of all parts of the engine, steam-pipes, and boiler from radiation and conduction of heat, the superheating of the steam when it has to travel a considerable distance, the arrangement of feed-water heater, the early opening of the eduction port to obtain a good exhaust, shallow piston packing with light pressure on it, large areas to bearings, provision for the plus and minus pressure of the piston, rod, beam, and connecting-rod due to momentum and inertia, &c.

About 1840 but few engines were burning as little as 7 lbs. of coal per HP. per hour, very many were using much more, though a few Woolf engines were down to about 4½ lbs.; Cornish pumping engines were decidedly below this.

Within the last ten years the consumption has been reduced to 2¼ and 1¾ lbs. by improvements in all directions, as well as by increased pressure of steam.

With effective mechanical stokers *small* good coal can be used with great advantage in London, being only half the price of good coal, as it is sifted out from it.

A HP. may now be produced in London at an expense of half a farthing per hour, and with a consumption of water equal to only one-third as much as is required for a high-pressure engine, if only a surface evaporative condenser be used.

Before concluding, I wish to express my obligations to those firms (amongst many to whom I applied) who have kindly sent models or drawings for exhibition to-night; many of them will be seen in the Library.

I have thus, however feebly, attempted to present to you a consideration of the manner in which, by utilizing by degrees the vast wealth of stored-up solar heat which we possess in our coal-fields, by simply varying the heat in water and steam and metallic bodies in a judicious manner, we obtain all the blessings that flow from these obedient giants, that thus are led to do our bidding in every conceivable manner.

I have sometimes considered what vast effects might have taken place, from some of our modern improvements and inventions, if they had been hit upon a few hundred years earlier; thus, if steamships had existed in early times, America would, no doubt, have been discovered many many years sooner than it was; if Cæsar had been possessed of a steam-navy, no doubt we should now all have been Romans. But the great and exceptionable good that steam-navigation has done for this country is incalculable in giving us the power of quick and cheap communication with every country on the surface of the earth, whilst we preserve intact our admirably safe position as an island, surrounded by a good sea; and when we consider the enormous amount of good that steam accomplishes in this country in our manufactures, and in giving us quick and cheap communication on land, it really almost seems as though the power of steam were an especial blessing, bestowed upon this nation by the Giver of all good things, and that thus fire and water, heat and cold, do really bless the Lord.

Sir JOSEPH BAZALGETTE, President, said they had listened to a very interesting and a very instructive lecture. They were all more or less familiar with the steam-engine, which did so much useful work in every department of life; but Mr. Cowper had followed its history from its first inception down to the present day. It was very remarkable to find that the first idea of the steam-engine should have been conceived before the Christian era; that it should have remained dormant so many centuries, and that its development to its present importance should have been left to the last hundred years. They had only to look at the diagrams to see how much time and care had been devoted by Mr. Cowper in working up the subject for the benefit of the members. He was quite sure not only that the lecture had been interesting to those who had heard it, but that it would prove of great interest to the whole body of the Institution for many years to come; he was also sure that the members would very readily accord to Mr. Cowper their best thanks, to which he was most thoroughly entitled.

There was also another vote of thanks, which he begged to propose, namely, to those gentlemen who had assisted Mr. Cowper and supplied the very valuable models exhibited in the Library, which they had kindly permitted to remain a few days longer for the inspection of the members.

Mr. E. A. Cowper said he was exceedingly obliged for the manner in which the members had listened to his lecture, and for the vote of thanks they had passed. It had been to him a labour of love, and it had certainly occupied him some time, but if it had been of the least use to the Institution in bringing the subject of the steam-engine more clearly before the members, he was thoroughly rewarded.

21 February, 1884.

SIR J. W. BAZALGETTE, C.B., President, in the Chair.

"Gas- and Caloric-Engines." [1]

By Professor FLEEMING JENKIN, LL.D., F.R.SS. L. & E., M. Inst. C.E.

MR. PRESIDENT AND GENTLEMEN—Allow me at the outset to express my deep sense of the magnitude of the task which is before me. It is impossible in a lecture of an hour and a half to treat the whole of this vast subject, and I must at once set aside all questions of mechanical detail. Nor shall I have much to say upon the subject of the history of caloric-engines. The point to which I wish to direct your attention chiefly to-night is the question of efficiency. But this word efficiency may be used legitimately in many senses. Before entering on the proper subject of my lecture, I will ask you to bear with me a few minutes while I make, or endeavour to make, clear what I mean by this word in each different sense. First, we may have what I will term the absolute efficiency; that is to say, the ratio between the indicated horse-power, I.HP., and the total quantity of heat, H, which is generated by the fuel per minute; this I will denote by the letter E; thus $E = \frac{\text{I.HP.}}{H}$. Secondly, we have in heat-engines what I will term the ideal efficiency and designate by the symbol E_i. This, as I have no doubt you have been told in previous lectures, is the ratio of the difference $\tau_1 - \tau_2$ of the absolute temperatures between which a heat-engine works, to the higher temperature τ_1. We cannot possibly, in any engine, convert more than this fraction of the total heat into work done on the piston. Thus $E_i = \frac{\tau_1 - \tau_2}{\tau_1}$. Thirdly, I may compare E with E_i; this may be termed the relative efficiency, and be designated by the symbol E_r. Then we have $E_r = \frac{E}{E_i}$. Fourthly, I may compare the work which a given engine might perform theoretically, according to an

[1] In consequence of the death of Professor Fleeming Jenkin before this lecture was fully corrected for press, his executor, Professor J. A. Ewing, kindly undertook its final revision.—SEC. INST. C.E.

indicator diagram calculated on certain hypotheses, with the heat generated by the fuel per minute. This I will call the theoretical efficiency of the engine, and will designate by the symbol E_t.

Thus
$$E_t = \frac{HP_t}{H}$$

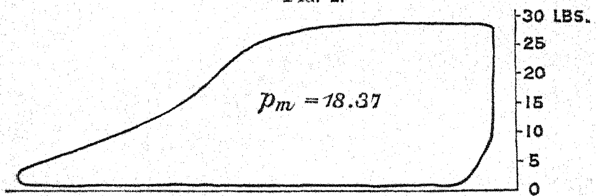
where HP_t designates the horse-power calculated as described. Then one may take the indicated horse-power, and compare it with the brake horse-power. This would be the mechanical efficiency of the engine; or one might compare the brake horse-power and the total quantity of heat generated, and in this way one might ring the changes upon the word efficiency until it would be difficult to follow the number of definitions. But I shall steer clear altogether to-night of what I have termed the mechanical efficiency, which is very important to the public, but with which we, in dealing simply with a heat-engine, have very little to do. The heat has done all that can be expected of it when it has given the power shown by an indicator diagram; and after that it is a question of mechanical efficiency and not of heat efficiency what the ratio may be between the indicated power and the actual brake power. In the discussion of Mr. Clerk's Paper on the gas-engine,[1] the word efficiency was used in different senses by different speakers, and this led to some confusion. I do not know what figures have been given you as measuring the efficiency of the steam-engine, but the actual values of E, the absolute efficiency, are easily calculated. If you take 2 lbs. per horse-power per hour, the value of E is something like 9 per cent.; if you take $1\frac{3}{4}$ lb. per hour it is 10 per cent.; if you take $1\frac{1}{2}$ lb. you have an absolute efficiency of about 12 per cent.; 12 per cent. of the heat supplied is then converted into mechanical effect. We start, then, in comparing the efficiency of heat-engines with these figures as known in the case of the steam-engine.

The first hot-air engine that appeared as a rival to the steam-engine, the first known to me at least, is the engine which was invented by Sir George Cayley, and described by him in Nicholson's "Art Journal," in 1807. A very full description of the engine in the form which it ultimately assumed appears in the patent taken out by Sir George Cayley in 1837. This engine is extremely like that which is now made and sold by the Caloric Company; to-night I shall call this the Buckett engine, of which a drawing is shown in Fig. 1, Plate 2. I have ventured slightly to distort Mr. Buckett's own drawings in order better to show the relations

[1] Minutes of Proceedings Inst. C.E., vol. lxix., p. 220.

between the different parts of the engine. At A we have a fire burning under pressure, and fed from time to time through the hopper B, which is closed by means of a valve R, so as to maintain the pressure within the furnace when the receptacle B is being fed with coals through the door T. The air required for combustion is delivered by the pump J, through the pipe H, and is divided, by means of the valve G, into two parts, one part going below the fire, the other going above it. The object of this distribution of air is to allow the engine-driver to promote combustion by sending more air under the fire and through the coals, or to check it by sending a larger proportion through the passage E into the space over the fire, where it may simply receive the heat from the products of combustion; if, however, the combustion of these is not complete, that is to say, if carbonic oxide comes up from the fire, this carbonic oxide will be, or may be, converted into carbonic acid on meeting the fresh supply of air introduced by the passage E. In the engine shown, the governor acts directly on the distributing-valve G. From the fire the heated air passes under the piston M,

FIG. 2.



BUCKETT ENGINE.

which it drives in the same way as the piston of an ordinary steam-engine is driven. P is the inlet valve, and O the exhaust. There is an ingenious arrangement in the present form of the Buckett engine by which the valve P is cooled.[1] The hot air, which presses against the piston M, is supplied at a temperature of from 900° to 1400° Fahrenheit, and is thus very much hotter than any steam delivered in a steam-engine. The indicator diagram which this engine gives is shown by Fig. 2 (woodcut). It is very like the ordinary diagram of the steam-engine; the power which you obtain from the engine is equal to the difference between the power calculated from that diagram and the power which is required to compress the cold air and force it into the furnace. In the engine as actually made, I am informed that the

[1] The valve seats of P are surrounded by an air-chamber, through which all the cold air pumped by J passes on its way to the valve G. This arrangement is omitted in the drawing.

consumption is 1·8 lb. of gas-coke per indicated horse-power per hour, or 2·54 lbs. per brake horse-power per hour, the HP. being calculated after deducting the work required to compress the air. The absolute efficiency is therefore either 10 per cent. or 7·9 per cent., as you compare the heat with the indicated or the brake horse-power. The actual consumption per HP. is, according to these statements, not very different from that of a good steam-engine, but the ideal performance of an engine of this class is very much higher than that of any steam-engine. If we were to take the upper limit of temperature even as low as 900°, and the lower limit of temperature as that of the air supplied, namely, about 100° Fahrenheit, we should find the ideal efficiency E_i to be something like 59 per cent., whereas the actual efficiency is only 10 per cent., or about one-sixth of the ideal. In other words, what I have called the relative efficiency $\frac{E}{E_i}$ is very small; and it is hard to say how in this form of engine we are to get any improvement. To my mind Mr. Buckett, in getting even so high an efficiency as this, has done extremely good work. The advantages aimed at in this engine are to avoid the loss of the heat which in a steam-engine passes away by the chimney, and secondly to gain the theoretical advantage due to working with a fluid of high temperature; but on closer examination it will be found that neither advantage is really obtained in actual practice. The cooling is wholly produced by expansion, and consequently the heat is rejected at a temperature of between 500° and 600° Fahrenheit when supplied at the temperature of 900°, or at about 900° Fahrenheit if it is supplied at a temperature of 1,400°. Thus, while on the one hand we might be led to expect very great improvement in the efficiency because of the very high temperature at which the hot air is supplied, we can easily see why we fail to realize this advantage, because simultaneously with the rise in the temperature of supply there is a rise in the temperature of rejection. The efficiency of the heat-engine depends upon the magnitude of the range through which the heat falls, from an upper to a lower temperature, and it is useless to increase the higher temperature unless we are able to keep the lower temperature down. Now since the cooling is effected by expansion alone, we can only lower the temperature of rejection by increasing the ratio of expansion. In the engines made by Mr. Buckett this ratio is two to one. The hot air is expanded to only twice its volume before being rejected. If the initial pressure instead of being 28 lbs. (which is the pressure used by Mr. Buckett,

as shown on the annexed diagram) were 100 lbs. per square inch, the initial temperature being 1000° Fahrenheit, and if we used a four-fold expansion, we should still have a final pressure above the atmosphere of about $1\frac{1}{2}$ lbs., and our final temperature would be reduced to something like 370° Fahrenheit, which is higher than that at which steam is supplied. The ideal efficiency would then be about 43 per cent. (Appendix II.). But in that case we should have great difficulties to contend with. First of all air is a much more difficult fluid to deal with than steam. The packing required to keep the cylinder air-tight, and all the parts of the pumps air-tight, is of a very different nature from that which is required in the case of steam, where the condensation of the steam greatly assists the packing. There is the further disadvantage in raising the pressure that a large percentage of the work would be employed in compressing the air for the furnace. Even in the case of the lower pressure actually used by Mr. Buckett, a very large amount of work is required to effect this compression. Theoretically, even when compressing only to 28 lbs., you would require to use nearly half the indicator diagram in compressing the air; actually, in practice, a little more than 50 per cent. is thus used. If you compressed up to 100 lbs. per square inch, you would require theoretically to use 65 per cent. of the work indicated in effecting this compression, and in practice a larger amount would be required. Where positive and negative work (as I may term work done by and against the engine) are performed alternately, and only the difference is useful, there is a sad tendency on the part of the positive work to diminish, and of the negative work to increase, so that the practical efficiency of an engine of this type is seldom found to come very close to the theoretical efficiency. I therefore have not any very great hope that the internal combustion engine supplied by coal in this way will become much more efficient than it has already been made. There is room for improvement, but the engine has now been known since 1807, and although the present example is certainly a very meritorious effort on the part of the makers, and one which will usefully meet certain special requirements, I cannot expect that the hot-air engine in this form will greatly surpass the performances of the ordinary steam-engine.

The internal combustion engine, however, is really the forerunner of the gas-engine, which is the most important form of caloric-engine now before the public.

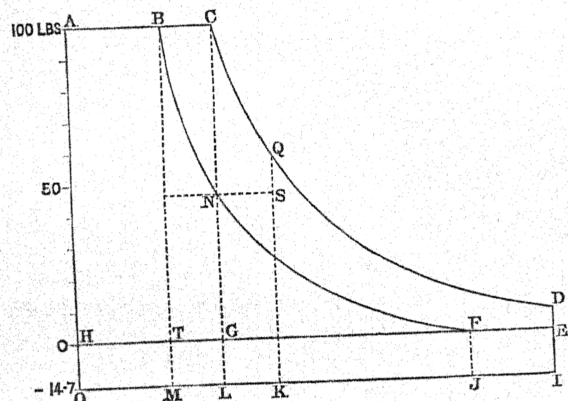
There is one difference in the theory of the gas-engine and of

the hot-air engine which I wish to make plain at the outset; the ratio of negative to positive work is essentially less in the gas-engine than in the hot-air engine. This will be obvious from an inspection of Fig. 3 (woodcut).

Let A B F H be the diagram of the compressing pump of a hot-air engine, and let A C D E H be the diagram of a working cylinder of the same diameter. The useful work done is indicated by the area B C D E F.

In a gas-engine, with the same maximum pressure and temperature, the compression of the gas and air would be indicated by the curve F N; the pressure would then rise suddenly to that indicated by C, and the expansion would be shown as before by the curve C D.

Fig. 3.



It is obvious by inspection that the negative work F N G done against the gas-engine is small relatively to the positive work G C D E, or the useful work N C D E F, whereas in the hot-air engine the negative work A B F H will often be actually larger than the whole useful work B C D E F. This disadvantage on the part of the Cayley-Buckett engine affects its mechanical efficiency rather than its theoretical efficiency as a heat-engine.

We have two forms of gas-engines prominently before us. There are many other meritorious makers, but I think I shall hardly be liable to contradiction when I say that of the gas-engines which are found practically at work, the largest number are made by Messrs. Otto and Crossley, and by Messrs. Thomson and Sterne, according to Mr. Dugald Clerk's plans. These are the two engines, therefore, which I shall chiefly consider to-

night. I shall not occupy much time in description, because I believe the action of these engines is generally known to most members of the profession. Fig. 4, Plate 2, shows a diagram of the working parts of the Crossley engine. It consists of a cylinder A, which is surrounded by a water-jacket M, for the purpose of keeping it at a reasonable temperature—a temperature in fact at which the oil on the surface can lubricate the piston. That I take to be the limit of the temperature at which the internal lining of the cylinder must be kept. The action of the engine is simply this:—The piston L is first of all employed in sucking in a supply of air and gas at the atmospheric pressure. This part of the action corresponds to the line H F of the diagram, Fig. 3; then the same piston compresses that charge of atmospheric air and gas up to the maximum pressure before ignition, which may be 40 or 60 lbs. per square inch. This action is indicated by the curve F N. The charge in the chamber A is then fired, the piston never going home as it does in the steam-engine. Owing to the increase of temperature due to combustion, the pressure rises (as indicated by the line N C, Fig. 3), and then the gas expands, driving the piston forwards during the working stroke of the engine. This part of the stroke is indicated by the curve C D. Then we have the return stroke of the piston, by which the contents of the cylinder are expelled. If we assume that there is no back-pressure beyond that due to atmospheric pressure, this part of the action appears on the diagram as the line E H; once only in four strokes (if I may call the backward and forward strokes two strokes) do we get a positive indicator diagram. This is a rough description of the action.[1] But the engine has many other peculiarities. One upon which the patentees and makers lay considerable stress is the power that it gives them of controlling the rate of combustion, so that they can modify the indicator diagram in the way which I am about to describe. You perceive that the piston in coming to the far end of its stroke does not expel the products of combustion entirely; there is a residual charge left in the cylinder. The new charge of air and gas is brought in behind this and presses forward not only the piston, but also this residual charge; the new charge is not necessarily a homogeneous charge. Air alone may be admitted at first, then a mixture of air and gas in any desired proportion, and finally a mixture richer in gas, so that it may be more easily ignited. It

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[1] Appendix III.

is believed that a very sensible stratification of this kind is produced and maintained; that you may at the moment of ignition have a charge rich in gas near the entrance; near the piston you may have merely the residual products not mixed with gas, and between those two places you may have gas and air, and gas and residual products in any proportion. Now this evidently gives us the means of controlling the kind of combustion which takes place in this engine. It can be shown by models that gas and air can be so delivered as to retain their places in a cylinder of this kind, and that you need not necessarily mix up the different parts together simply into a diluted mixture of the residual products with air and gas. In some forms of the Crossley engine I think there can be little doubt this stratification exists in a very marked way. In others I am not so clear that the stratification is always present, but it is obvious that you have in this residual charge which is left in the engine a means of controlling the richness of the mixture, and it is highly probable that the last portion of the gas and air which enters the cylinder will be rich in gas and easily ignited, whereas that portion of the gas and air which has been previously introduced will to some extent mix with the residual products; this diluted mixture will ignite after it has been heated by the explosion of the first portion; so that whether mixed or not we are pretty certain to have complete combustion, and this complete combustion does, I believe, take place very satisfactorily in the Otto and Crossley engine. I do not think that for the excellence of its behaviour it depends wholly or even mainly upon the maintenance of the stratification as so many distinct bands, provided we have first a rich mixture which is easily fired, capable of acting almost explosively so as to fire the rest of the material, which can be more or less diluted.

The Clerk engine (Appendix III.) is extremely similar as regards the theory of its action. I am not sure that the makers of these two engines would agree with me upon this point, but so far as I am able to form any opinion, I should say that the action of the two engines was extremely similar, and that we should expect to find, as we do find, a very close agreement between the actual results which are obtained. In the Clerk engine, however, there is a totally different method of introducing the gas and air, and a very ingenious one. A (Figs. 5 and 5A, Plate 2) is the cylinder; C is the piston. The charge of gas and air is introduced through the valve V, by a passage not shown, and goes into the chamber G. When it comes in, the residual products of combustion are driven

out before the incoming charge through the exhaust E, until a portion of the incoming charge follows the residual products through the exhaust. This portion is intended by the makers to be simply air. As soon as that begins to go out through the exhaust, we have the cylinder completely emptied of the residual products which Messrs. Otto and Crossley retain. Then the exhaust is closed, and after that the charge of gas and air is compressed by the return of the piston C into the chamber G, ready for firing. The action of the engine is then exactly similar to that of the Otto and Crossley engine. The difference, and it may possibly turn out to be a very important difference, is this: that in the one case you have the residual products retained, for the purpose of diluting the mixture, and in the other case you have no residual products retained for the purpose of diluting the mixture. Moreover, in the engine designed by Mr. Clerk we have the air and gas delivered into the cylinder by means of a displacer piston D at every second stroke, instead of at every fourth stroke, and this is so far an advantage; but on the other hand this is counterbalanced by the fact that you have to add to the engine another organ, namely, the pump or displacer B which sucks in the air and gas in the first instance, and then delivers it, acting, not against the pressure, but simply as a displacer, into cylinder A. But in both cases we have the simple explosion or burning, if we choose so to call it (perhaps it is more correct to call it burning), of a charge of air and gas, or of a charge of gas mixed with air and residual products; the burning charge expands according to the laws of fluids in a closed chamber of varying volume, and in both engines this burning charge does work by expanding, and gives rise theoretically to the very same indicator diagram. There may be small differences between the two engines, due to the different proportions of the cylinder, but the two theoretical indicator diagrams must be very closely the same. It does not appear that there is any very great difference in the manner in which the combustion takes place, whether the dilution of the charge is due simply to air, or to the residual products.

Now I come to another burning question. About two years ago an admirable Paper was read by Mr. Clerk upon the theory of the gas-engine. There was an excellent discussion upon the Paper, and a great deal of that discussion turned upon the question whether, during the burning of the gas, dissociation acted as a check to the pressure and temperature which were arrived at. I need hardly say that I have studied that Paper carefully. I have also been much favoured by Mr. Clerk and Messrs. Crossley, who

have both shown the greatest kindness in providing me with the results of any experiments which I chose to ask them to make, and in giving me the benefit of experience far greater than my own, teaching me, in fact, many of the things of which I have to speak to-night. It seems to me that those experiments show that although the words they would use in describing the effects are different, as to the effects themselves which are to be anticipated in any given case, they would both be in agreement; as must be the case, in fact, when two independent observers simply wish to ascertain the truth. I will describe the results of some experiments which were tried first of all at my suggestion. The point raised seems to have been this: does the combustion take place gradually in the Otto engine in consequence of the stratification which is assumed to exist? Now, I will put altogether on one side the question of stratification; the important question, it appears to me, is rather, does the combustion take place gradually, or have we a rapid combustion almost completed at the very beginning of the stroke? Let us put out of the question altogether the causes which may effect the result, and simply consider the result. Now, about this I think there can be absolutely no doubt whatsoever. There are a series of diagrams here, furnished by Mr. Crossley, which show, in the most conclusive manner, that by varying the strength of the mixture you can vary the rate at which the heat is produced. First of all we have a set of diagrams asked for in the discussion of two years ago, and as they are amongst the least conclusive diagrams, I will take them first—a set of diagrams lettered A (Fig. 6, Plate 3), showing the effect of change of speed when the mixture is kept as nearly constant as possible. It is by no means an easy thing to keep the mixture constant. The amount of air sucked in varies with the speed, and varies with the temperature of the cylinder, and it is extremely difficult to ascertain. I can hardly feel certain that any experiments have been tried—certainly none have been brought before my notice—in which in an absolute manner the weight of air supplied to the engine was practically known. It can only be inferred, whereas the quantity of gas is really measured. But trusting to Messrs. Crossley's experience, we may suppose that the charge really was maintained constant at these different speeds. It will be seen that as the engine runs slower and slower, so the initial pressure rises higher and higher; and in this case the higher pressure certainly corresponds to a higher temperature. One must be warned against always imagining that a higher pressure in the gas-engine corresponds to a higher temperature. That depends

upon whether or not the actual fluid which is being heated remains the same in quantity and quality; we might have a higher pressure and a lower temperature, if the density of the original mixture were raised. But here if the mixture was really maintained the same—and the best efforts were directed to make it the same—then we have a rise of pressure, and consequently of temperature, due to a reduction in speed. It must be remarked that the rise is very small, and therefore that, even at the faster speeds, we had got very nearly to the maximum temperature and the maximum pressure at an early period of the stroke. This set of diagrams, then, is not very conclusive as to whether or not there is some limit set by a dissociation of the gases, both to the temperature and to the pressure. Again, it leaves rather uncertain the question as to whether or not there is a gradual combustion taking place. The next set of diagrams, lettered B (Fig. 7, Plate 3), were taken to show the effect of a change of mixture, and here we have a very much more marked result. We find that as the mixture is made richer and richer, we get a higher and higher initial pressure. In this case again it is not absolutely certain that the higher initial pressure corresponds to a higher temperature, because we are not certain that the same weight of fluid is contained in the cylinder at the moment of explosion; but any variation in the weight of the original fluid must have been small, so that I think the diagrams do point distinctly to a rise of temperature as the richness of the mixture is increased. This can hardly be doubted, and if so there is no sign that a limiting temperature has been reached. It is no doubt open to question, whether if there be a limit this limit is set by dissociation at one temperature for one mixture, set at a higher point by dissociation for another which is richer in gas, and set at a higher point by dissociation for a third which is richer still. There is some good ground for supposing that something of this kind will take place, nevertheless these results of experiments are at any rate consistent with the assumption that there is no limiting pressure approached yet by the gas-engine and fixed by means of dissociation. These diagrams also leave the question open as to what the rate of combustion might be. But when we come to the diagrams lettered C (Figs. 8 and 9, Plate 3), taken from an engine in which a very weak mixture was burnt, I think there can be no doubt whatever that such diagrams as these correspond to a very slow rate of combustion; that we have, in fact, the combustion taking place throughout the whole stroke. There were some diagrams shown here upon the occasion to which I have referred in which it would appear as if ignition had been

delayed, as if at the beginning of the stroke the gas had not in fact caught fire, and this was called slow inflammation, distinguishing it from slow combustion. But in Diagram C I think there can be no doubt that combustion is taking place throughout the whole stroke.[1] Moreover this conclusion is supported by this other Diagram D (Fig. 10, Plate 3) taken from a Crossley engine in which a partition had been placed, which separated the incoming gas and air from the residual products, so as to prevent the dilution of the charge. In diagram A, which is the normal diagram, the curve is blunt at the top. In diagram C we find that the curve is very much sharpened. We have a sudden increment of pressure and temperature at the very beginning of the stroke, due as it would appear to the richness of the mixture and the rapidity of the combustion; and then we have a comparatively sudden fall, not differing much however from the ordinary adiabatic curve. Now these results all point to slow combustion in the case of the Crossley engine, whether you have mixture or stratification between the residual products and the incoming gas and air. And it does appear to me that this conclusion is not only amply supported, but absolutely established by the very interesting experiments which have been communicated to me by Mr. Dugald Clerk. Indeed I am not at all sure that Mr. Clerk, although some of his expressions bear that interpretation, would ever have contradicted the assertion that combustion was taking place gradually throughout the whole stroke of the Otto and Crossley engine, and also throughout the whole stroke of his own engine.

The results of experiments which I have the honour of showing to-day, for the first time, are only a small part of a much more ex-

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[1] *Note by the Editor.*—Mr. Crossley has kindly furnished the following supplementary explanation of Figs. 8, 9, and 10.

The curves of Fig. 8 and Fig. 9 are indicator diagrams of *successive* explosions or combustions of a weak mixture of air and gas, the proportion of gas to air being constant. "In Fig. 8 (says Mr. Crossley) the changes are due, I believe, to imperfect combustion. In the smaller diagrams less gas was *burnt* than in the bigger, though the same quantity was *admitted*. The next ignition consumes some that was left from the time before. The striking difference between Fig. 8 and Fig. 9 is due to stratification being more complete in Fig. 9 than in Fig. 8, *i.e.*, the richer portion of the charge lies nearest or nearer the light in Fig. 9 than in Fig. 8; so that though the same quantity only of gas is present, it is more effectively ignited and utilized in Fig. 9 than in Fig. 8." The proportion of gas to air in the total charge is the same in Fig. 9 as in Fig. 8.

"Fig. 10 shows the effect of too perfect a stratification. Combustion is here too much accelerated to be economical. The quantity of gas is not increased, as in Fig. 7, but merely its distribution through the charge is altered by a diaphragm in the cylinder."

tended series of experiments made by Mr. Clerk, and they seem to me to be of the highest interest. They are represented by the two diagrams E and F (Figs. 11 and 12, Plate 3). These show the result of the following experiment. There was a closed cylindrical vessel 7 inches internal diameter, 8¼ inches long, filled with definite mixtures of gas and air, or of simple hydrogen and air. Then when completely shut in (there is no working piston) the mixture was fired by an electric spark. There was a little indicator piston attached to the cylinder, in a way which all engineers will readily understand, which traced these indicator diagrams upon a drum revolving uniformly. Taking hydrogen first, Diagram E (Fig. 11), we have curve *a*, corresponding to one volume of hydrogen and six volumes of air; curve *b*, one volume of hydrogen and four volumes of air; and curve *c* for the rich mixture of two volumes of hydrogen and five volumes of air. We find in curve *a* a slow rise of pressure and temperature, and in curve *c* a very quick rise. We find the combustion taking place rapidly in the one case and gradually in the other. There is no doubt whatever from this diagram that the combustion does take place more slowly in the one case than in the other. Diagram F (Fig. 12) shows similar results when different mixtures of coal-gas and air are burned. We see here a still more extended series showing that the time of attainment of maximum pressure is completely under control according to the greater or less dilution of the mixture. If you will notice the number of seconds you will see that even the rich mixtures take six hundredths of a second before the maximum pressure is reached; that is quite comparable with the time taken by the piston of an actual engine in moving through a very appreciable part of its stroke. The gradual fall of pressure indicated is due to no other cause than to simple conduction away of the heat by the sides of the vessel. But when that removal of heat by the sides of the vessel is eliminated as well as it can be, it will be very apparent that combustion is going on after the maximum pressure is reached. In the experiments indicated by some of these curves the combustion is proceeding at nearly a constant rate before and after the point of maximum pressure. The fact of gradual combustion is absolutely proved in these beautiful and, as far as I know, novel experiments of Mr. Clerk.

They present also one very remarkable feature, to which I will draw your attention, although it may have greater interest for the physicist than for the engineer. In the case of hydrogen, you will observe that the curve in each instance rises in an unbroken line from the starting point to the point of maximum pressure; whereas

in the case of the combustion of coal-gas, there is a very singular hump in the middle. This is not due to the indicator, which is the same in both cases; moreover we have a less rapid increase of speed of indicator piston in the case of coal-gas than in the case of hydrogen. It is not therefore an oscillation due to some inertia in the little indicator by which the curve was traced; it represents a real pause in the rate of combustion, due, one would imagine, to the variety of elements which go to form the whole of the gas. The very complicated substance coal-gas may behave very differently from the simple substance hydrogen. We may have certain hydro-carbons being decomposed at this period, and the amount of energy required to do that may cause a very sensible check in the rate at which the curve rises.

We have, then, in the whole group of experiments tried by Messrs. Crossley and Mr. Clerk ample evidence to satisfy us that the combustion takes place gradually in all cases; and, moreover, that we have the power of controlling this rate of combustion as we please by diluting the materials, whether they are stratified or not. I do not know that any experiments have been tried by Mr. Clerk with gas which has been diluted by mixture with the residual products, but I should expect closely analogous results to follow. No doubt one may say that in certain forms of engine, inflammation takes place very rapidly, and combustion slowly, and that in other forms inflammation takes place slowly and combustion rapidly; but it is exceedingly difficult, to my mind, to separate the two things. There is no doubt a difference between the idea of the propagation of the flame from one part of the cylinder to the other by the gradual catching fire of successive layers, and the idea of gradual combustion which takes place after the flame has really spread throughout the mass; but I confess to feeling the greatest uncertainty as to what takes place inside the cylinder after the ignition occurs. There is not the slightest doubt that the rate of increase of pressure is under control by the dilution of the mixture. There is also no doubt that it is under control by the manner in which that mixture is fired; that you may propagate the flame more rapidly by shooting out a mass of lighted gas into the middle of the mixture. You may modify the rate of combustion in both cases, whether the gases are stratified or not; and the main thing for the bulk of the profession, I take it, is to know that we have two means of modifying the manner in which this combustion takes place.

Now there is no advantage, from any heat-engine point of view, in the gradual combustion. So far as gas-engines are

heat-engines it would be more advantageous that the whole heat should be given at the higher temperature and, therefore, at the beginning of the stroke. But this might and would have an inconvenient practical result by giving us pressures with which it would be inconvenient to deal: we should have great strains on many parts of the engine. Therefore it is desirable that we should be able to delay the rate of combustion. It is quite certain, whether dissociation sets a limit or whether there is some other cause, that the maximum temperature reached in the gas-engine is practically very much alike in all the forms of engine—that it does not differ very much from 1,530° or 1,500° Centigrade. I find the various authorities agreeing upon that. It is not of any very great consequence whether that limit is set by dissociation, or whether it is set by some other cause, we must acknowledge the fact, and design our engines with the knowledge of the fact; and we may feel thankful that we do not get the whole of the heat produced at once, because this would give rise to those inconvenient pressures of which I have spoken. Here again I find the most absolute agreement between the makers of the two engines. In a most interesting Paper submitted to me by Mr. Crossley and written by Dr. Slaby, of Berlin (see Appendix IV.), there is a calculation of the quantity of heat developed at the time when the maximum pressure is produced in the cylinder. According to that calculation it is about half the total heat: the rest of the heat is developed during the stroke. Whether the exact proportion is right or not, I cannot say; it depends upon a good many assumptions as to specific heat and so forth, but roughly it must represent the truth. Exactly in the same way, Mr. Dugald Clerk, in calculating the quantity of heat developed by the hydrogen curve at the point of maximum pressure, arrives at the same conclusion—that there is about one-half of the heat present as heat at that point, the rest being developed afterwards. And this gives rise to a very much more convenient indicator diagram than we should otherwise have. If all the heat were developed at once we should have a high initial pressure followed by a rapid fall, whereas with the actual mode of combustion we have a well-sustained pressure throughout the stroke without any very extravagant amount at the beginning.

In dealing with this combustion it hardly appears to me that the phenomenon is as simple as has been supposed. At the instant when the pressure is greatest, this pressure is found to be that which would correspond to a temperature of 1530° Centigrade if all the fluid were at one temperature; but when we think what

must happen inside the cylinder, we see that the outer layers next the cold water must be comparatively cool, that we shall have an extremely hot kernel, as it were, in the very centre of the cylinder, and that we shall have successive layers separating this very hottest portion from the colder portions; that we shall have extremely rapid convection between these different parts, but still in the main we must have an extremely hot kernel and a comparatively cool envelope outside. The expansion which will occur under these circumstances must altogether defy calculation. We shall have the centre expanding and giving up its heat to the surrounding parts; we shall have other layers of fluid expanding and receiving heat throughout the stroke from the hotter portions of the fluid; we shall have, moreover, layers of fluid which are parting with heat rapidly to the metal outside; and we only observe upon the indicator diagram the gross result of all these extremely complicated changes. No doubt this gross result is comparatively simple. With the degrees of expansion which are used in these gas-engines, the actual curve which is observed differs very little from that known as the adiabatic curve, which supposes that no heat is given and none taken away. That supposition is absolutely contrary to what we know takes place in the case of the gas-engine. We are, as I shall show you, taking away by the cooling envelope one-half of the whole heat which is generated, but on the other hand heat is supplied by the gradual combustion at such a rate that the curve obtained in practice may be taken as sensibly coinciding with the adiabatic curve, the result being the same as we should find if we had a smaller quantity of heat produced, but kept it inside an envelope which was perfectly non-conducting, and retained the whole heat.

So much as regards the theory of the burning. As to the practical results which the great makers have obtained, we find that Messrs. Otto and Crossley, speaking of their new twin-engine (in which two such cylinders as I have described are placed side by side, so that there is an explosion once for every revolution, and which works up to about 28 HP.), claim the remarkably high mechanical efficiency of 82 per cent. This is the ratio between the brake horse-power and the indicated horse-power. For each I.HP. they consume about 20 cubic feet of gas, or for each B.HP. they consume about 24·3 cubic feet. The space required by the engine is very small; 10 feet 8 inches by 4 feet 8 inches; the speed from one hundred and fifty-five to one hundred and sixty revolutions per minute. This is the last result they have obtained. When they burn, instead of the ordinary coal-gas, the Dowson gas (the merits of which were

explained not long since by Mr. Dowson, who has, moreover, since then simplified his machinery), they have a consumption of 1·1 lb. of coal per I.HP.—only half that of very good steam-engines. Besides these general results, an extremely elaborate analysis of the performance of one of these engines is given in the report drawn up by Dr. Slaby of Berlin (Appendix IV.). I cannot agree with everything he has stated in that document, but the experimental part bears every sign of having been conducted with the greatest care, and I think it is extremely instructive. The general result is this: the engine was consuming about 28·3 cubic feet of gas per I.HP. (it was only a 4-horse engine), and this is a poorer result than that which Messrs. Otto and Crossley are now able to secure. With this engine 16 per cent. of the whole heat generated was converted into I.HP., 51 per cent. of the total heat was taken away by the cooling due to the water which surrounds the cylinder. Here is a great margin, as you will observe, for improvement in the future of gas-engines. The expelled products took away 31 per cent., and there remains only the small amount of 2 per cent. lost by general conduction and radiation. It will be observed that more than half the heat was taken away in a manner which is absolutely useless. This is not finding fault with the engine, but simply stating the fact that the heat taken away by the cooling water is absolutely wasted so far as efficiency is concerned; the only object of the cooling jacket is to keep the oil in the cylinder at a temperature which enables the engine to run with due lubrication. The heat liberated before the maximum pressure was reached was 55 per cent. of the whole. The maximum temperature (calculated in a somewhat circuitous manner) was 1231° Centigrade. The mean temperature of the discharged products was observed to lie between 423° Centigrade and 432° Centigrade. The average effective pressure was about 54 lbs. per sq. in., the maximum pressure 156 lbs. per sq. in.

The results which were obtained from a Clerk engine are closely analogous to these. The I.HP. is 9·71; the B.HP. 7·7. The mechanical efficiency is 79 per cent., which is as high as any one can reasonably expect. The maximum pressure is 206 lbs. per sq. in. The amount of gas per I.HP.[1] is about the same as in Messrs. Otto and Crossley's engine, 20·6 per I.HP., and 26·3 per B.HP. Certain other engines of Mr. Clerk have given even more favourable results, coming as low, under rather exceptional

[1] That is, per HP. indicated in the main cylinder.

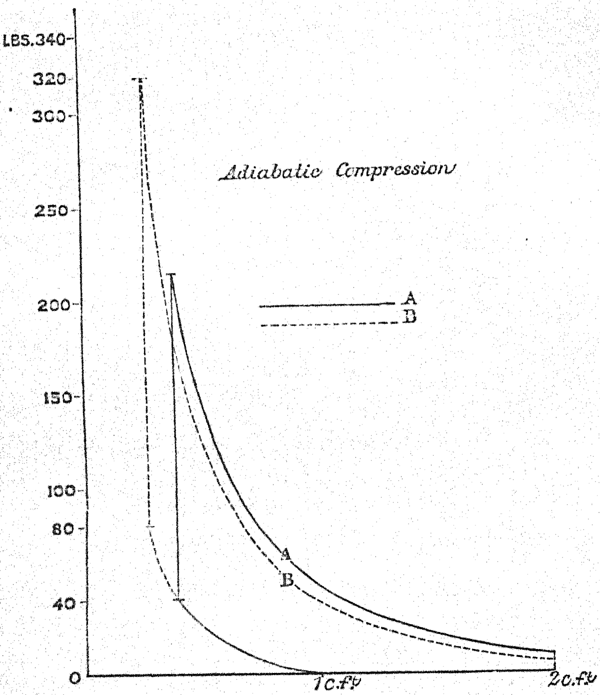
circumstances, as 17 and even 15 cubic feet per I.HP. But since, in my judgment, the theory of the two engines is very similar, the consumption per I.HP. is likely to be identical, and any difference in the practical working will depend on points of which we cannot treat to-night. Mr. Clerk, by a completely separate and independent experiment, found that in his engine 54 per cent. of the total heat generated was taken away by the cooling water. The experiment by Dr. Slaby of Berlin gave us almost exactly the same result. We may confidently say, therefore, that more than half the heat generated is wasted in this way. This 54 per cent. is the quantity of heat, or one of the quantities, which we might possibly save by fresh invention. No previous results with gas-engines have equalled those which I have quoted. We may measure the great advance made by looking back to what was done by the original Lenoir engine, in which there was no compression of the gas and air before ignition. Then only about 4 per cent. of the total heat generated was converted into B.HP., according to the data given by Prof. Tresca; that would be less than one-third of what was done during Dr. Slaby's experiment, in which more than 14 per cent. was converted into B.HP. If we take the better results which have since been achieved in the larger engines by Mr. Clerk and Mr. Crossley, apparently 16 or 17 or even 18 per cent. of the heat generated is by them converted into B.HP. We have, therefore, at least a fourfold improvement as compared with the original Lenoir engine. That corresponds very much with what we find if we look simply to the consumption of gas. The original engine consumed about 90 cubic feet per I.HP.; then it was improved until it consumed something over 70 feet. Now we have an engine which consumes 20 feet or even less per HP., and we have not yet got near the limit beyond which improvement is impossible; this last point is really important in estimating the merits of these gas-engines. When we are dealing with other forms of heat-engines we find that we are getting somewhat near the limit of perfectibility. When I am told that the steam-engine is very perfect, then I say, so much the worse for the steam-engine, because nothing more can be done for it. But every imperfection that I am able to point out in the gas-engine is a point in its favour. It shows the margin there is for improvement. Nevertheless, what is the result? Why, we can already speak of 24 per cent. of the heat actually generated being converted into work in the cylinder. I should say that that was quite double what has been done by steam-engines with which I am acquainted. I have not looked at

the very latest results obtained from steam; but certainly the absolute efficiency of the actual gas-engine is double that of the steam-engines that I myself happen to have studied.

Now that I have spoken so well of the gas-engine, the next point for consideration is to compare the ideal efficiency and theoretical diagrams with the actual efficiency and real diagrams that we obtain, and here we shall at once begin to be extremely dissatisfied with the performances of the actual engine. We find that the burning gas reaches a temperature of 1530° Centigrade, and in some parts of the cylinder the temperature may not improbably reach 1900°, because, as I ought to have said, Mr. Clerk is clearly of opinion that the temperature of 1900° was reached during those experiments in closed vessels. That 1900° should be reached for an instant in the perfectly-closed vessel is not at all inconsistent with the fact that in a cylinder with large cooling surfaces surrounded by water the maximum pressure should be that corresponding to 1530° and not 1900°. I have already pointed out that a mean temperature of 1530° throughout the cylinder at a given moment requires that at the kernel of the mass the temperature should be considerably greater, and we may from Mr. Clerk's experiment take this maximum as at least 1900°. Now if we calculate the ideal efficiency of a heat-engine working between the limits of say 17° Centigrade and 1900° or even 1530°, we shall see that it is very greatly in excess of what we get in the case of the actual engine. It would, however, be unfair to take the ideal efficiency of the engine calculated in this way. In the ideal heat-engine it is necessary that all the heat should be given at the highest temperature and rejected at the lowest. Is that the case in the gas-engine? Certainly not. The heat is received by the fluid at all points, from the temperature which the gas has when we set fire to it up to the temperature which it ultimately reaches. We cannot take any one temperature as representing the true temperature at which all the heat is given. In the same way, when the heat is rejected we do not reject the whole heat at the temperature of the atmosphere nor even at the lowest temperature of the residual products, neither do we reject it at the temperature which these products have when the exhaust is first opened; we reject it at a number of intermediate temperatures, ranging from the highest temperature reached to the temperature when the exhaust is about to close after the return stroke. Therefore the gas-engine does not present the features of an ideal engine at all, and I must not compare the actual results attained with the results of an ideal engine, working between the two extreme conceivable limits. It may interest me

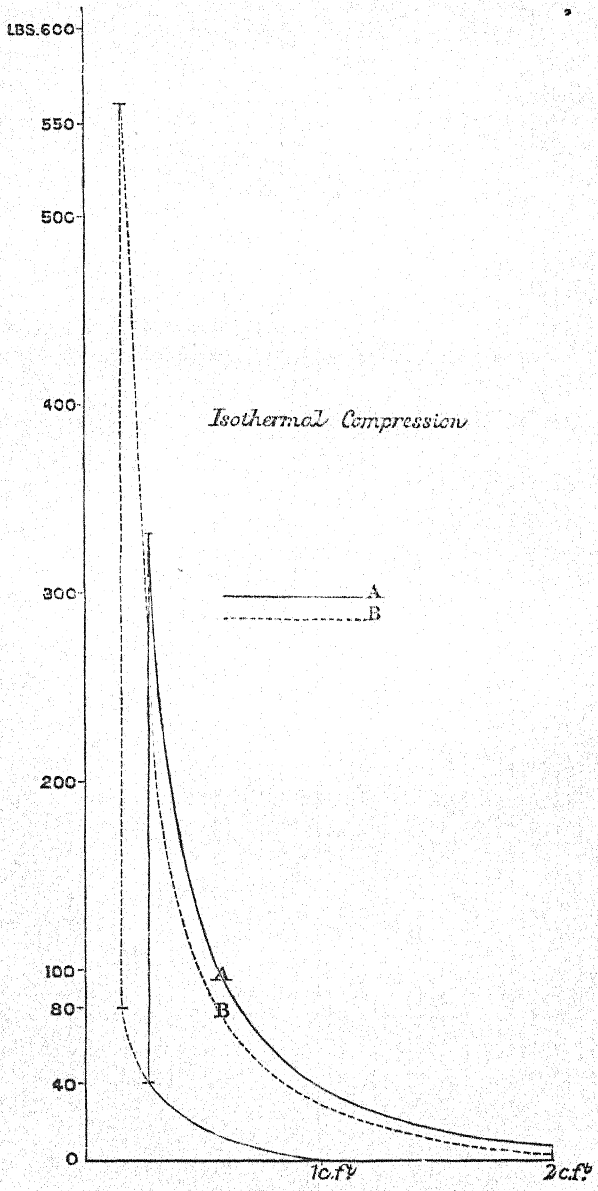
to make the comparison, but it is of no practical importance. I cannot with our actual engines expect to approach this ideal engine. What I must do before I can see what the difference is between the observed performance of the engine and that which I have a right to expect from it, is to calculate the *theoretical* efficiency, by which I mean the efficiency as determined from the theoretical indicator diagram which an engine would give provided certain not wholly impossible conditions could be observed;

FIG. 13.



that is, provided I gave all the heat at the period most advantageous from the heat-engine point of view, and then kept the whole heat in, not taking any out through the cooling envelope, but allowing the gas to expand along the adiabatic curve, and then rejecting it finally and instantly. Fig. 13 gives two theoretical diagrams of this kind lettered A and B, showing air admitted to the cylinder of a gas engine at atmospheric pressure, compressed until it reaches a pressure of 40 lbs. and 80 lbs.

Fig. 14.


LBS. 600
550
500
400
300
200
100
80
40
0
1c.ft.
2c.ft.
Isothermal Compression
A
B
A
B

respectively, heated suddenly to 1,537° Centigrade, and expanded to double its original volume. This diagram is what I call theoretical; I mean by that word that certain important facts are left out of account; (that is my definition of theoretical. For the sake of simplicity, you leave out a number of considerations which you know to exist, and having done that you call the result theoretical, and the smaller the number of facts you leave out the closer will be the coincidence between the actual result and the result of theory). Now when I so compare the theoretical and the actual performance of the engine, I find something of the following kind. If I were to compress gas to 40 lbs., a pressure which is used not unfrequently, the theoretical efficiency would be 45 per cent.[1] We actually get something like 24 or 23 per cent.; we know that one-half of the heat is taken away by external cooling; thus we find a very close coincidence between the calculated efficiency of these engines and that which we actually obtain; only we throw away about one-half of the heat in keeping the cylinder cool enough to permit lubrication. If we compress to 80 lbs. we have a theoretical efficiency of 53 per cent. If we do not compress at all, as Mr. Clerk has told you, we have a theoretical efficiency of only 21 per cent., so that we have it in our power to increase the theoretical efficiency very greatly by increasing the pressure of the gas and air before ignition. I have no doubt that the great gain of efficiency in the Clerk and Otto engines is really due to the fact of the compression; this being done in a workmanlike way and carried to a very considerable extent. But there is very little hope of getting much beyond the point already attained. As you increase compression you increase the difficulties of construction immensely, and we can hardly expect much further improvement by the use of higher and higher initial pressures. In my opinion this principle has already been pushed almost as far as is practicable with actual materials and actual finish of workmanship. An idea occurred to me which I thought might be worth investigating, the results of which I only give for the purpose of saying that the idea is worthless. It was clear that the efficiency of the engine as a heat-engine might be improved by lowering the temperature at which heat is rejected, and it occurred to me that this end might to some extent be attained by cooling the air while it was being compressed; and it is interesting to compare the results of theoretical diagrams computed on this supposition with those computed upon the supposition (which cor-

[1] Appendix II.

responds closely with actual practice) that the fluid is compressed without any abstraction of heat, so that the compression curve is adiabatic instead of isothermal. The result is shown in the diagrams, Fig. 14. These are theoretical indicator diagrams, calculated with the following data.[1] One volume of air, say a cubic foot, at atmospheric pressure, is compressed to 40 lbs. and 80 lbs., as shown by full and dotted lines. Sufficient heat is then supposed to be added to raise the temperature to 1537° Centigrade; this temperature is chosen to make the results comparable with those of Mr. Clerk's paper; the fluid is then expanded to two volumes, say two cubic feet, and instantly discharged into the atmosphere. In Fig. 13 the compression is effected without any abstraction of heat, so that the compression curve is adiabatic. In Fig. 14 the compression is effected so that during compression the fluid remains at one temperature; the compression curve is isothermal. The efficiencies are as follows:—

Adiabatic compression to	40 lbs.,	efficiency	0·45.
,, ,,	80 lbs.,	,,	0·52.
Isothermal compression to	40 lbs.,	efficiency	0·48.
,, ,,	80 lbs.,	,,	0·54.

The efficiency is therefore hardly changed at all, but the isothermal compression gives a distribution of pressures far less suited for practice than that given by adiabatic compression. The maximum pressures above the atmosphere are 218 lbs. and 328 lbs. respectively for the two adiabatic diagrams, and for the isothermal compression these pressures have risen to 325 lbs. and 574 lbs. These high pressures are quite inadmissible, and this is the less to be regretted as the gain of efficiency is insignificant. We may therefore reject the idea of isothermal compression as worthless. Then what remains? There are two perfectly distinct faults in the gas-engine as it stands to-day: first, that the temperature of rejection of the burnt gases is a great deal too high; and secondly, we lose a large proportion of heat across the walls of the cylinder. I will deal with these separately, taking first the question of the lowering of the temperature of rejection. The more you can expand, the more you cool by expansion, and you can lower the temperature of rejection in this way. That is the heat-engine explanation of the merit of initial compression. But we have got pretty nearly to the end of the gain which can be obtained in this way.

Then comes the perfectly distinct idea of in some way or other

[1] Appendix II.

making use of a regenerator. The first use of the regenerator which I have been able to find (I shall be glad to be corrected if I am wrong) is in Stirling's first patent for a hot-air engine.[1] That patent was taken out in 1827, and it is one of the most remarkable documents that I know in the history of engineering. I do not think that engineers are by any means sufficiently acquainted as a body with the extraordinary merit of the invention made by Dr. Robert Stirling, a Scotch minister, who was assisted by his brother, James Stirling, an engineer. The regenerator is really one of the greatest triumphs of engineering invention. The fundamental idea connected with the regenerator is that it is a means of storing and re-storing heat without losing it. It allows you alternately to raise and lower the temperature of a mass of air or water, or whatever fluid you choose, without losing (theoretically) any of the energy. Practically some portion of the energy would be lost at each change. This storing and re-storing of heat is playing a larger and larger part in the industry of the country, and all honour should be given to the name of the man who first proposed the regenerator. I believe that man to be Dr. Robert Stirling. His idea has been much more fertile in other directions than in the actual improvement of any heat-engine. No doubt that idea has been greatly favoured by falling into the hands of so able a man as the late Sir William Siemens (I do not know whether it occurred to him independently or not), who passed a great part of his life in endeavouring, in many cases successfully, to adapt the regenerator to various branches of industry. The patents for gas-engines which were taken out by Sir William Siemens from first to last form a remarkable body of documents. I cannot attempt to give a summary of them. I have no doubt, that if a few more years had been given him he would have attained success with these engines, but so far, no one of these engines has ever come into practical use, and the firm has been unable to give me any details of the actual results obtained. Nevertheless, the very fact that such a man spent so many years of his life in endeavouring to adapt the regenerator to the internal-combustion engine, must show what I believe to be certainly the truth, that in that idea lies the future of internal combustion in general; that by the application of the regenerator we shall be able so much to lower the temperature of rejection as in a marked manner to increase the efficiency of the engines. The original Stirling engine is shown in Figs. I. to VI., Plate 4,

[1] Appendix VII.

but the essential parts are more easily seen in the diagram, Fig. 15, Plate 2, after a sketch in Rankine's well-known "Manual of the Steam Engine," or in Fig. 16, Plate 2, which shows Robinson's engine, a small but complete form of the Stirling engine now in the market, driven by gas used externally. There is a plunger F (Fig. 16) which works up and down inside the vessel A, acting simply as a displacer. The cylinder A has a driving-piston C connected with the crank E; a second crank at right angles to the first, and in advance of it, works the displacer. When the displacer is at the top of its stroke the greater portion of the air is in the lower space over the furnace B, and is heated. There it will expand, occupying a larger volume than when cool, and if the piston C is at the bottom of the stroke it will be impelled towards the top. Then the plunger F comes down and moves the air up through the regenerator of wire gauze, which forms part of the plunger F, as in Stirling's original patent (*vide* Appendix VII., and Fig. 15A, Plate 2). The air reaches a refrigerator A_2, which is a mere water-jacket in Robinson's design, and it is cooled there; then the air contracts and the piston C comes down. We have thus simply alternate expansion and contraction of the same body of air, and the engine will obviously be driven. The theory of the engine is sufficiently stated by Rankine in his Manual.

The great merit of Stirling's engine lies in the regenerator. We have a great change of temperature taking place without any great loss of heat. The air receives heat when it is hot; it then goes out from above B hot, it enters the regenerator hot, it comes out at the other end of the regenerator cooled; it then loses heat while cold. Remark that the main change of temperature is not effected by the refrigerator. The refrigerator takes away heat which is thus rejected at the lowest temperature. When the air passes back down the regenerator the heat which it previously gave up is restored, and the fresh heat which is added afterwards by the fire is added at the highest temperature. You have, therefore, a theoretically perfect heat-engine, every portion of the action of which is reversible, and reversibility, as you have no doubt been told in previous lectures, is the test of a perfect engine. Stirling's is a perfect engine, and it is the first perfect engine ever described. You have here one and the same man devising an engine which is theoretically perfect, and devising the regenerator.

He was followed at a considerable distance by Ericsson. I shall not describe his engine, which forms another variety of the perfect heat-engine with a regenerator. The idea which naturally

occurs is that by this time the Stirling engine ought to be more common, especially seeing that it has a cool working-cylinder and piston although it takes advantage of extremely high temperatures in the receiver. But the practical difficulties are obvious. You have the furnace outside, and all the heat is transmitted through a metal plate with no safeguard against overheating; there is therefore a constant danger of burning out the bottom of the receiver. There is a further difficulty in providing sufficient heating surface. The result has been that this engine has not multiplied, except on a comparatively small scale. We find in the market a certain number of engines which may be called Stirling engines (I hope the English makers will not mind my so calling them, just as I may call a steam-engine a Watt engine. I do not say that their particular designs have not great merit in themselves, but they are all Stirling engines). One of these, shown in Fig. 17, Plate 2, is that made by Mr. Bailey. It is, like that of Messrs. Robinson, an arrangement in which you have the displacer and piston in one line—that is a compact way of making a Stirling engine. The long surface between the displacer E and the outer casing D acts as a regenerator. (A diagram taken from Mr. Bailey's engine is shown in Appendix III., Fig. 27.) Fig. 18, Plate 2, gives an illustration of the little Rider engine, introduced from America by Messrs. Hayward, Tyler and Co. In this engine the plunger C corresponds to the displacer F of the true Stirling engine, and the piston or plunger D is the working piston. The two are so connected that when C is near the bottom of its stroke, and the fluid is consequently chiefly under D receiving heat and expanding, the piston D is rising; when again this piston falls, the plunger C is near the top of its stroke, so that the air is chiefly in the cold space under C; heat is then being rejected, and the fluid contracts. The passage of the fluid from one cylinder to the other takes place through the regenerator H, so that theoretically no loss occurs during the change of temperature. All these points the engine has in common with that of Stirling, but Mr. Rider allows the hot air to press directly against the working piston, which seems a step in the wrong direction. All these engines are simply used for small powers, 1, 2, or 3 HP.; beyond that they become unmanageable. Although the results obtained by Bailey and Robinson are really very favourable, nevertheless one can see that there is small probability that we shall obtain a large and efficient heat-engine so long as the heat is applied outside. Naturally the idea which will occur to every one is that we should burn gas inside the vessel A above the plate B

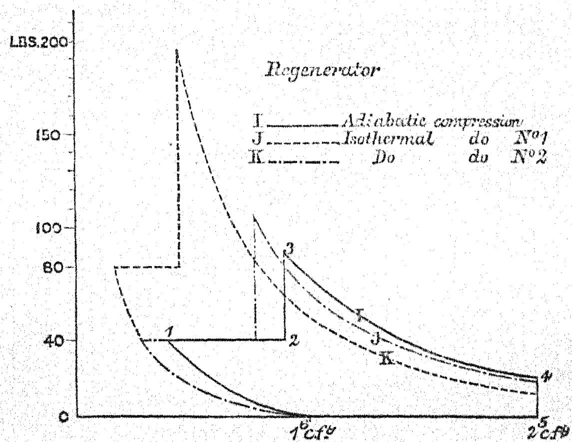
(Fig. 15), that we should have our fire inside instead of outside. The problem at first sight appears to be exceedingly simple; some (not all) of the ideas of Sir Wm. Siemens were distinctly in this direction. I myself, beginning with great ignorance of the subject, made some experiments in that line, which lasted over a considerable number of years, the first being conducted by myself, and then in conjunction with Mr. A. C. Jameson, first my pupil, then my assistant, and now co-operating with me in various ways. We soon found out the great difficulties that exist in applying this idea. They are much more numerous than would appear at first sight. The first one is that of ignition; but with a certain amount of trouble that can be got over. Then comes the difficulty that before a Stirling engine can be made practically efficient you require to have high pressure. If you have not high pressure the engine must be extremely bulky relatively to its power, because your mean pressure throughout the stroke is extremely small. In the little engines which have been described, one great merit of which is simplicity, there is no attempt made to get high pressure, because adding a force pump would add greatly to the cost and complication, and the saving of a few pounds of coal would be comparatively of no importance. But for large engines you must have such pressures as Stirling used (150 lbs. per square inch is the minimum pressure mentioned in his second patent), and when you have to deal with air under such a pressure you meet with great difficulties. You require to compress it probably by two steps, to have two compressing-pumps. Then there is the further complication, that you require to expel at each stroke as much gas and air as you put in. The total amount of working fluid is very much larger than that; so that you are dealing with a mass of residual products, and you only want to burn or explode a little thimbleful of gas and air at each stroke in the middle of these products—a fresh difficulty. Then, notwithstanding the small amount of air and gas which is to be burned, if you do not wish to throw away the work employed in compressing it, you have to use it expansively in an ordinary cylinder, more or less after the manner of Mr. Buckett or Mr. Wenham. Then, inasmuch as each cylinder is only single-acting, if you require a double-acting engine, you have two displacers, two cylinders, a little relieving-cylinder, a double compressing-pump, and so forth, and you find that the engine is not in the least adapted for anything except large sizes, and you have complication enough to deter any one from continuing the experiment. Then there is a third difficulty, the difficulty of clearance. I use the word as

Rankine used it. If you are to burn the gas inside a Stirling engine, you must line the receptacle with some refractory material which shall not conduct heat to the outside. You require to insulate your heat. Now, in all small engines you would require to put in an enormous thickness of this refractory material, because you cannot reduce that thickness in proportion to the other dimensions of your engines; you need an immensely thick lining, in order to keep the heat in, and the loss by radiation, whether you burn gas or solid fuel, would be very great. And that is not all. Another difficulty that turns up is this, that the moment you put in your refractory material you introduce a large amount of clearance or waste space into the engine, due to the porosity of the material. That is a thing for which we were not in the least prepared when we began the experiments. Any increase of clearance in a Stirling engine causes the mean effective pressure to fall very greatly. Well, the refractory materials are so porous as greatly to increase this clearance. How porous they are, very few persons know. We found that the fireclay used for crucibles had 30 per cent. porosity, some fire-bricks as much as 58 per cent., and few less than 30 per cent. The very densest specimen gave 15 per cent. porosity, and 15 per cent. of the volume of this extremely thick lining augments the clearance beyond all management. We made an effort to overcome this, and we did, to some extent, successfully overcome it, by putting in what we called a separator, that is to say a metal lining, which separates the great bulk of the refractory material from the internal portion. Fig. 19, Plate 2, shows a section of the furnace displacer and regenerator, which we last tried with some success. The place where coke was burnt is shown at K. The displacer F has a metal covering everywhere except at the lower face where the fire impinges, there we used fire-bricks. The furnace was fired through the opening A by means which need not be described. The rods forming the regenerator are seen at G. The main separator is lettered B, and it will be seen that it divides the spaces filled with refractory non-conducting fire-brick into two portions, of which the inner has much the smaller capacity. The clearance is still further diminished by enclosing other portions of brick or brickdust in distinct casings as at L. The refrigerator is seen at D. By this design the clearance was got within manageable limits. But there remained all the other difficulties, and the conclusion that we came to was this, that whereas in the future internal-combustion engine of the Stirling type less fuel would be employed than in any other, nevertheless this type of engine was unsuitable for small simple engines, and that to develop the larger sizes a very large amount

of capital would be required, larger than we were disposed to put in at the time.

One is therefore driven to consider whether there is really no other mode in which the regenerator could be applied; and in thinking of what I could lay before you it occurred to me to consider what the result would be of simply passing the fluid in and out through a regenerator. That is, taking the air and gas through a regenerator into the cylinder so as to be heated before being fired, and afterwards, instead of rejecting the gases straight into the air, passing them out through the regenerator and so cooling them—which seems a perfectly simple and natural way of using the regenerator. I will now deal with this purely theoretical idea. Sir William Siemens had very much the same idea in a

FIG. 20.



provisional patent which he abandoned, and something like the same idea is to be traced in several other patents, but I cannot find that any attempt has been made to utilize it. The indicator diagrams, Fig. 20, have been calculated for an ideal engine of this type (*vide* Appendix II.). In the smallest of the three diagrams (that marked I) we have one volume, say one cubic foot, of fluid, compressed in a pump with no abstraction or addition of heat until a pressure of 40 lbs. above the atmosphere is reached. Then the fluid is supposed to be displaced at a constant pressure, passing through a regenerator heated by the previous discharge. This part of the diagram is indicated by the horizontal line 1, 2; the temperature meanwhile rises, and the fluid expands, doing work. This expan-

sion is in the diagram supposed to be continued until 17·5 British thermal units have been restored by the regenerator (per cubic foot of the original fluid). Then 19·2 thermal units are added to raise the temperature to the assumed limit of 1537° Centigrade. When the pressure indicated by Point 3 is reached, the fluid is allowed to expand, neither losing nor receiving heat until it occupies two volumes, say two cubic feet. This expansion is shown by the curve 3, 4. The theoretical efficiency calculated from the diagram thus obtained is 56 per cent., that is to say, such an engine would convert 56 per cent. of the heat of combustion into I.HP. The diagram marked J is calculated on the assumption that heat is abstracted in the compressing pump so that the temperature of the fluid shall not rise; the same quantity of heat as before is taken as stored and re-stored. The theoretical efficiency on this assumption is 54 per cent. The largest diagram, lettered K, shows the effect of increasing the pressure from 40 to 80 lbs. The efficiency calculated from this diagram is no less that 72 per cent. In all these cases the heat rejected in the fluid at the pressure and volume reached at the end of the stroke, added to the heat converted at each stroke, is equal to the whole heat of combustion during each stroke. The amount of heat that can be stored or re-stored is limited by the consideration that the regenerator can only abstract such a portion of the heat left in the rejected fluid when the exhaust opens as will cool it to the temperature of the fluid as it enters from the pump. Practically, of course, the whole of this heat could not be stored, but only a part of it. The idea as now presented to you is admittedly crude, for no attempt has been made to carry it into practice, and there are some obvious difficulties in the way. Nevertheless the idea seems worthy of study, for the result of the calculation shows that we should obtain a very high efficiency if it could be carried out, and this high efficiency is not the only advantage. The maximum pressure at the limiting temperature is much reduced. This of itself is a great gain. We also have a more uniformly distributed pressure throughout the stroke; in other words the maximum and minimum pressures are much nearer to the mean pressure than in any other diagram; moreover the maximum pressure occurs when the crank is at a favourable angle. Even, however, if we could construct an actual engine with a regenerator placed as I suggest we should not strike at the root of the worst evil. The worst evil is that so large a proportion of the heat is led away through the sides of the cylinder, and very little has been done to remedy this up to the present moment. I am not quite at one with Mr. Clerk

concerning the Otto and Crossley engine when he says that this engine necessarily loses more heat than his own by conduction through the walls of the cylinder. It seems to me that the two engines are in this respect nearly upon a par, but if anything I would give the palm to the Otto and Crossley. I have not time to give the reason, I merely record my opinion.

Mr. Foulis, of Glasgow, is attempting to avoid the loss of heat across the walls of the cylinder, by lining the gas cylinder with refractory fire brick, and so burning the gas in a chamber which is red hot. In that way there is no doubt he may prevent the conduction of heat through the walls of the cylinder: but unless there is some special device for lowering the temperature of rejection, he will simply increase the temperature of rejection and will not find so great a gain as he expects.

His plan has, however, not been completely explained to me, and he may have some method which is not known to me, of getting over this difficulty. An ingenious suggestion has been brought before me by my colleague, Mr. Jameson. He proposes to apply stratification in a different way. His object is during each successive stroke to coat the walls of the cylinder with cool air which is not explosible. When the explosion takes place he intends to make such arrangements that stratification is retained; you then have a cold cushion of the best non-conducting material against the walls of your cylinder. He will lose the heat taken up by the cold air cushion at each stroke; but the heat thus necessarily lost at each stroke, it seems to me, would not be nearly so great as that which in existing forms is conducted away through the metal walls of the cylinder. If this idea, like several others I have mentioned, is somewhat crude, I must ask for your forgiveness, on the ground that I am not dealing with a subject which is thoroughly worked out; I am dealing with a subject which is rapidly growing. Whether there be any merit or not in the suggestions I have made, it is quite certain that there is much room for improvement in two directions. We may hope to save part of the heat now taken away by the cold-water jacket round the cylinder, and we may hope to save part of the heat rejected in the products of combustion; fresh inventions are, however, required before these improvements can be effected. When Dowson gas is applied, as it now may be with no great difficulty, I feel no doubt that even for large engines the gas-engine as it is now made may compete upon favourable terms with the steam-engine. Since that is the case now, and since theory shows that it is possible to increase the efficiency of the actual gas-engine two- or even three-fold, then the conclusion

seems irresistible that gas-engines will ultimately supplant the steam-engine. The steam-engine has been improved nearly as far as possible, but the internal-combustion gas-engine can undoubtedly be greatly improved, and must command a brilliant future. I feel it a very great privilege to have been allowed to say this to you, and I say it with the strongest personal conviction.

Sir Joseph Bazalgette, President: It is my pleasing duty to propose a vote of thanks to Professor Fleeming Jenkin for the very able and interesting lecture to which you have listened. I am sure you will all agree with me that he has shown himself to be a master of the subject with which he has dealt. He would not have been able to lay it before you in so clear a manner as he has done without a considerable amount of labour, and although there are many gentlemen here who are familiar with the gas-engine, I venture to think that none will leave this room to-night without having gained some idea which will be of value and give room for further thought.

The vote of thanks was carried by acclamation and was acknowledged by Professor Jenkin.

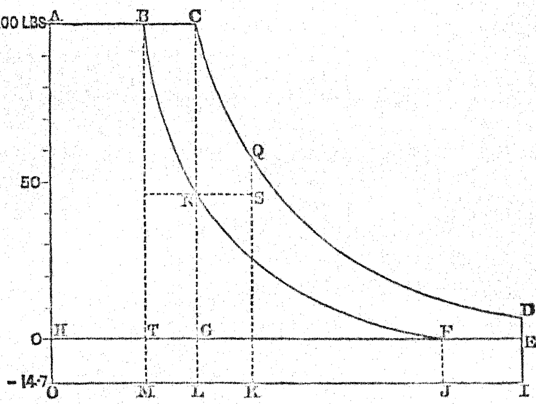
[Appendix.

APPENDIX I.

Notation, Formulas, and Constants.

The following abstract of the relations between pressure, volume, temperature, weight, heat, and work done, is given in the hope that it may be found useful by engineers:—

Fig. 3.



1. *Notation.*

P, absolute pressure in pounds per square foot (strictly speaking this should be termed intensity of pressure).

P_b, P_c, &c. When a letter is suffixed in this way, it is intended to signify that the pressure referred to is that corresponding to the ordinate ending in the diagram, Fig. 3, at a point designated by the letter suffixed. A similar suffix to other symbols, such as those for volume or temperature, has a similar meaning.

$P_{c\,d}$. When two letters are suffixed in this manner, the symbol denotes the mean absolute pressure (in pounds per square foot), calculated from the curve beginning and ending at the points C and D in the diagram, Fig. 3.

V denotes the volume in cubic feet occupied by 1 lb. of air or other gas.

V_f, V_b, &c., designate the volume occupied by 1 lb. of air or other gas when the pressure is P_f, P_b, &c.

$\frac{1}{V}$, mass of 1 cubic foot of air or other gas in pounds.

r, ratio of the volume occupied by air or other gas before expansion to the volume occupied by the same air or gas after expansion.

$r\begin{cases}c\\d\end{cases}$ The letters and bracket affixed in this manner signify that the ratio is taken for the volumes V_c and V_d.

r is also used to signify the ratio of the volume after compression to the volume before compression.

τ signifies absolute temperature in degrees Fahrenheit.

t signifies temperature as measured by the ordinary Fahrenheit thermometer.
$\tau = t + 461 \cdot 2$, according to Rankine.
$\tau = t + 459 \cdot 4$, according to later physicists.

H, a quantity of heat in foot-lbs.—given to 1 lb. of air or other gas.
h, a quantity of heat in British thermal units—given to 1 lb. of air or other gas.

The British thermal unit is the quantity of heat required to raise 1 lb. of water of maximum density 1° Fahrenheit. The following numbers give the relation between the B.T.U. and other heat-units approximately. Great confusion exists in the units at present adopted, partly due to the large number of fundamental units employed, partly due to the adoption of different temperatures as standards, and partly due to the use of 1 lb. as a unit of force. The adoption of the C.G.S. system offers the only escape from this confusion; but at the present moment the use of that system would render this Paper of little value to practical engineers.

J denotes Joule's equivalent, *i.e.* the number of foot-lbs. of work which are equivalent to one British thermal unit.

In Rankine's treatise—

1 British thermal unit = 772 foot-lbs.
(Based on experiments by Joule.)

According to later researches by Joule—

1 British thermal unit is more nearly = 773·1 foot-lbs.,

where the pound is the force due to gravitation acting on the mass of 1 lb. at Greenwich, at sea-level.

According to those physicists who take 424 as the number of kilogrammetres in a calorie (*i.e.*, the amount of heat required to raise 1 kilogram of water of maximum density 1° Centigrade),

1 British thermal unit = 772·8 foot-lbs.

Approximately 1 B.T.U. = 0·252 calories (kilogram-degree Cent.)
1 B.T.U. = 252 gram-degree Cent.
1 B.T.U. = 10480 megergs (C.G.S. units $\times 10^6$.).

-H, The negative sign affixed to the symbol for heat, denotes that the heat is withdrawn from the pound of air or other gas instead of being added.

U, Useful work done by 1 lb. of air or other gas, as computed from the theoretical diagram for a given engine.

2. *Atmospheric Pressure.*—When comparing results obtained by different authors using this expression to denote a standard intensity of pressure, care should be taken to ascertain what meaning they attach to the expression.

Most writers take atmospheric pressure as that corresponding to 760 mm. of mercury at 0° C., though some writers take 30 in. of mercury at 0°. If a standard height of mercury in the barometer be assumed, then at any one place the actual pressure in terms of force per unit of surface depends on the specific gravity of mercury and the value of g at the given place. The values assigned

to the specific gravity of mercury have varied considerably within the last twenty years, and this introduces one element of uncertainty.

When authors explain, as Rankine does, that the "atmosphere" to which they refer corresponds, say, to 2116·4 lbs. per square foot, it must be remembered that the pound used as the unit of force is the force exerted by gravitation on 1 lb. mass at the sea-level at Greenwich, and that the force exerted at Glasgow or Berlin on the same mass will be actually different, so that the pressure corresponding to 760 mm. of mercury would be different at the three places, and would require to be expressed by different numbers if expressed in terms of any constant unit of force. The mass of 1 lb. of air under atmospheric pressure corresponding to 760 mm., would therefore be different at the three places. Moreover, the ratio between the forces called pounds and kilograms in France and England, is not the ratio between the masses, although this fact is almost universally ignored. All ambiguity could be avoided by taking the dyne as the unit of force, and one megadyne per square centimetre as the standard atmospheric pressure. This standard corresponds to 2087 lbs. per square foot, or 749·64 mm. of mercury at 0° C., both at the sea-level at Greenwich.

The constants given in this Appendix are calculated on the assumption that the unit force is that exerted by gravitation on the mass of 1 lb. at the sea-level at Greenwich, and the standard atmosphere is taken as corresponding to 2116·4 lbs. per square foot.

In all examples calculated, Rankine's constants have been adhered to; these are quite sufficiently accurate for engineering purposes.

3. *Relation between the Pressure, Temperature, and Volume of 1 lb. of Air or other Gas.*

1°. $$P\,V = R\,\tau.$$

R is a constant for each gas or mixture of gases. A Table is appended giving the value of R for several of the more important gases. This constant obviously depends on the position of the absolute zero of temperature (strictly speaking, the position of the absolute zero is inferred from the observed value of the constant). The value given in the second column is most nearly true; the values in the first column have been given to allow Rankine's constants to be employed consistently. Thus for air we have—

$$P\,V = 53{\cdot}15\,\tau.$$

The constant R is the work in foot-lbs. done by 1 lb. of air or other gas when expanding under constant pressure, while its temperature is raised 1° Fahrenheit.

This follows directly from expression 1°; for let 1 lb. of gas at pressure P expand from the volume V_1 to the volume V_2, while its temperature changes from τ_1 to τ_2 (or t_1 to t_2), we shall have—

$$P\,(V_2 - V_1) = R\,(\tau_2 - \tau_1),$$

and obviously $P\,(V_2 - V_1)$ is the work done by the expanding gas.

Expression 1° serves to find V, the volume of 1 lb. of air or other gas at any pressure and temperature; or to find $\frac{1}{V}$, the weight in pounds of 1 cubic foot of air or other gas at any pressure and temperature.

TABLE I.—VALUES of CONSTANT R in EXPRESSION 1° for VARIOUS GASES.

Gas.	R if $\tau = t + 461\cdot2$.	R if $\tau = t + 459\cdot4$.
Dry air	53·15	53·35
Oxygen	48·08	48·25
Nitrogen	54·72	54·92
Hydrogen	767·4	770·2
Carbonic acid	34·76	34·89
Carbonic oxide	55·68	55·88
Marsh gas	94·55	94·90
Manchester coal-gas, 30 cubic feet per pound at atmospheric pressure and $t = 62\cdot6°$ Fahrenheit	121·2	121·5
London coal-gas, 35·5 cubic feet per pound at atmospheric pressure and $t = 62\cdot6°$ Fahr.	143·6	144·1
Dowson gas (Minutes of Proceedings C.E., vol. lxxiii., p. 320)	63·7	63·9

4. *Specific Heat.*—Let K_p denote the specific heat of a gas at constant pressure; that is to say, let K_p be the quantity of heat in British thermal units required to raise the temperature of 1 lb. of the gas 1° Fahrenheit while it is maintained at constant pressure (for which purpose it must be allowed to expand and so do external work).

Let K_v denote the specific heat of the same gas at constant volume; that is to say, the quantity of heat in British thermal units required to raise 1 lb. of the gas 1° Fahrenheit, while the volume remains unchanged but the pressure rises (so that no external work is done).

Note that K_v and K_p are expressed by the same number in the British pound degree Fahrenheit system, as in the kilogramme degree Centigrade, and in the gramme degree Centigrade systems. These numbers may be defined as ratios between the heat required by the gas, and that required by the same weight of water for the same rise of temperature.

The following relation is shown by experiment to connect K_p, K_v, R, and J.

2°. $$R = J\,(K_p - K_v).$$

It has already been shown that R is the work done by 1 lb. of the gas, while expanding at constant pressure and rising 1° Fahrenheit; this work is now shown to be also equal to the difference between the specific heats at constant pressure and at constant volume for the same gas. In other words, the work done by 1 lb. of the gas while expanding at constant pressure and being heated from τ_1 to τ_2, is (in foot-lbs.) equal to the excess of heat required by the pound of gas to heat it while expanding and doing work, beyond that which would be required to heat it from τ_1 to τ_2, when, the volume remaining constant, no work is done.

This law shows that the heat supplied to an expanding gas does no internal work on the gas itself.

The following Table gives the specific heats of various gases and their ratio. Column 1 headed K_p is taken from a table in Everett's "Units and Physical Constants," based on Regnault's experiments.

The values of K_v in column 3, are calculated from column 1, by expression 2°, which gives $K_v = K_p - \frac{R}{J}$.

J is for this purpose taken as equal to 772·8, and R is taken from the second column of Table I.

Columns 2 and 4 are calculated from 1 and 3 with J = 772·8.

The ratio $\frac{K_p}{K_v}$ is required in subsequent calculations, and is denoted by the symbol γ.

TABLE II.—SPECIFIC HEATS.

Name of Gas.	1 K_p in British Thermal Units.	2 K_p in foot-lbs.	3 K_v in British Thermal Units.	4 K_v in foot-lbs.	5 $\frac{K_p}{K_v} = \gamma$.
Dry air	0·2375	183·5	0·1685	130·2	1·409
Oxygen	0·2175	168·1	0·1551	119·9	1·402
Nitrogen	0·2438	188·4	0·1727	133·5	1·411
Hydrogen	3·409	2635	2·412	1865	1·413
Carbonic acid	0·2163	167·2	0·1712	132·3	1·264
Carbonic oxide	0·2450	189·3	0·1726	133·4	1·419
Marsh gas	0·5929	458·2	0·4701	363·3	1·261
Products of combustion of gas and air, the relative volumes before combustion being 1 : 8·18 (Grashof and Slaby)[1]	0·264	204·0	0·192	148·4	1·375
		Rankine's Constants (for dry air).			
R = 53·15 J = 772	K_p B. T. U.	K_p foot-lbs.	K_v B. T. U.	K_v foot-lbs.	γ
	0·238	183·7	0·169	130·47	1·408

From K_p we calculate the heat required to change the volume of 1 lb. of gas expanding as from V_b to V_c in the diagram.

From K_v we calculate the heat required to raise the pressure of a gas as from P_a to P_c in the diagram.

The heat required to produce both a change of volume and a change of pressure depends upon the particular mode in which the expansion or compression takes place; in other words, upon the relation of P to V during the operation. It may be calculated by finding the external work done and adding to that the quantity $K_v\ (\tau_2 - \tau_1)$ where τ_1 is the temperature at the beginning of the operation and τ_2 the temperature at the end.

5. *Law of Adiabatic Expansion or Compression.*—Let the curve C D (Diagram, Fig. 3) be the line bounding ordinates which represent the pressure of a given mass of gas when expanding and doing work, but neither receiving nor emitting heat. This curve is termed *adiabatic*, and expansion under these conditions is called adiabatic expansion. The same curve will of course represent the law of compression by work done upon the gas, while it neither receives nor emits heat during the process. This will be termed adiabatic compression.

Let P_1 and V_1 be a coincident pressure and volume, let P_2 and V_2 be any other coincident pressure and volume resulting from adiabatic expansion or com-

[1] For other mixtures see Appendix V. for Grashof's formulæ.

pression, then the law of adiabatic expansion or compression is expressed as follows:—

3°. $$P_1 V_1^{\gamma} = P_2 V_2^{\gamma},$$

where the exponent γ has the value given in Table II.: in other words $P V^{\gamma}$ is constant.

Let $r = \frac{V_2}{V_1}$ be the ratio of expansion, then the above law may be written

4°. $$P_1 = P_2 r^{\gamma}.$$

For dry air with Rankine's constants this gives $P_1 = P_2 r^{1 \cdot 408}$.

This expression serves to calculate the ordinates of the expansion or compression curves in the theoretical diagrams, where no means are supposed to be employed to heat or cool the gas during the process: by taking successive values of r corresponding to successive values of V_2 any number of points in the curve are found. The indicated expansion curve in actual gas-engines is found closely to resemble the adiabatic curve, although a large amount of heat is withdrawn during the process. This proves that combustion is continued throughout the stroke.

6. *Mean pressure calculated from the Adiabatic Curve.*—Let P_{cd} be the mean absolute pressure for that part of the curve which begins at C and ends at D, and let r be the ratio of the final to the initial volume, *i.e.*, let $r = \frac{V_d}{V_c}$; then we have

5°. $$P_{cd} = \frac{P_c (1 - r^{1-\gamma})}{(r-1)(\gamma - 1)}$$

For air with Rankine's constants this becomes

$$P_{cd} = \frac{2 \cdot 451 \, P_c}{r-1} \left(1 - \frac{1}{r^{0 \cdot 408}}\right).$$

Similarly we may calculate P_{cd} from the lower pressure P_d. We have

6°. $$P_{cd} = \frac{P_d (r^{\gamma} - r)}{(r-1)(\gamma - 1)}.$$

Or for air with Rankine's constants

$$P_{cd} = 2 \cdot 451 \, P_d \left(\frac{r^{1 \cdot 408} - r}{r-1}\right).$$

Expression 5° is most convenient when we use the gas to do work by expanding; expression 6° is most convenient when we do work upon the gas by compressing it. The total work done by or done upon 1 lb. of the gas is obviously

$$(V_d - V_c) P_{cd}.$$

But this expression takes no account of the back pressure, which in the theoretical gas-engine is at least that of the atmosphere (2116 lbs. per square foot), or of the assistance which, on the other hand, the atmospheric pressure gives when we are compressing the gas. Thus

7°. $$U_{cdeg} = (P_{cd} - 2116)(V_d - V_c),$$

where U_{cdeg} is the actual useful work done per lb. of air in a theoretical gas-engine (whose piston is exposed on the other side to the atmosphere) while ex-

panding from V_c to V_d, or the actual useful work required in the same engine to compress it adiabatically from V_d to V_c, the work, that is, corresponding to C D E G. Obviously, V_f and V_n, or any other volumes, may be substituted for V_c and V_d.

7. *Change of Temperature during adiabatic Expansion or Compression.*—If a gas while expanding is not allowed to do work its temperature will neither rise nor fall. Joule proved this by the following experiment: Two vessels A and B were connected by a tube and stopcock; air was forced into A until a pressure of say 20 atmospheres was reached; a vacuum was formed in B. The whole apparatus was plunged into a vessel of water, and left there till the whole was at a uniform temperature. The stopcock was then opened; the air rushed from the one vessel to the other until at equal pressure in both vessels. No appreciable change of temperature occurred. But in this case the expanding air did no external work. The law of expansion was not that which we have called adiabatic, one condition of which was that the gas should do work, as by pressing forward a piston. When the expansion is adiabatic, the temperature falls during expansion and rises during compression. Let τ_c be the absolute temperature of a pound of gas when its volume is V_c, and let τ_d be the absolute temperature of a pound of the same gas when its volume is V_d after adiabatic expansion. Thus—

8°. $$\frac{\tau_d}{\tau_c} = \left(\frac{V_c}{V_d}\right)^{\gamma - 1} = \left(\frac{1}{r}\right)^{\gamma - 1},$$

or for air with Rankine's constants,

$$\frac{\tau_d}{\tau_c} = \left(\frac{1}{r}\right)^{0.408}.$$

We may write this law of the change of temperature conveniently as follows:—

9°. $$\log \tau_d = \log \tau_c - 0 \cdot 408 \log r,$$

10°. $$\log \tau_c = \log \tau_d + 0 \cdot 408 \log r,$$

where expression 9° is that by which we most conveniently calculate the fall of temperature due to expansion, and expression 10° is that by which the rise of temperature due to compression is calculated.

8. *Law of Isothermal Expansion or Compression.*—Let the curve C D (Diagram Fig. 3) be the line bounding ordinates which represent the pressure of a given mass of a gas when expanding and doing work, and receiving from without so much heat as maintains the temperature of the gas constant. This curve is termed isothermal, and expansion under these conditions is called isothermal expansion. The same curve will of course represent the law of c mpression by work done upon the gas, while heat is withdrawn from it at such a rate as keeps the mass at a constant temperature. Let the constant temperature be τ, then $P = \frac{R\tau}{V}$ (expression 1°) gives the pressure corresponding to each volume occupied by a pound of the gas. The pressure is inversely proportional to the volume occupied by the given mass (Boyle's law). This shows the isothermal curve to be a common hyperbola. Let as before U_{cd} be the total work done by a pound of the gas when expanding from V_c to V_d (the curve being now isothermal), and let H be the total heat (measured in foot-lbs.) supplied to the pound of gas to maintain its temperature constant during the process. Then we have

11°. $$H = U_{cd} = \overline{LCDI}.$$

That is to say, in order to prevent any change of temperature, we must supply heat exactly equivalent to the work done. Similarly, when isothermal compression is employed we have to abstract heat equal in amount to the work done in compression if we desire to prevent any change of temperature. The amount of heat required is calculated by the following expression:—

12°. $H = R \tau \text{ hyp} \log r$; or, using common logarithms,

13°. $$H = 2 \cdot 3026 \, R \tau \log r.$$

For air with Rankine's constants this expression becomes

$$H = 122 \cdot 38 \, \tau \log r.$$

It follows, from expressions 11° and 13°, that the mean pressure is given by the following expression:—

14°. $$P_{e\,d} = \frac{2 \cdot 3026 \, R \tau \log r}{V_1 - V_2}.$$

It must be remembered that this is the mean absolute pressure, and in calculating the useful work done by an expanding gas, or the actual work required to compress a gas, allowance must be made for the atmospheric pressure, as explained above in the case of adiabatic expansion and compression.

9. *General remarks.*—The formulas given assume that real gaseous fluids conform to a certain ideal state assumed as constituting a perfect gas. Probably no real gas behaves in this ideal manner, but the discrepancies between the ideal and the real gas with such volumes and temperatures as engineers usually employ are not of such magnitude as to be of practical importance.

It is difficult when running a gas-engine to ascertain precisely what mixture of gas and air is being employed. The air as it enters is heated, and we cannot tell how much. It would be necessary in precise experiments to run the air through a meter as well as the gas.

Heating power of various samples of coal-gas:—

	Foot-lbs. per Cubic Foot.	Foot-lbs per lb.
Manchester coal-gas	505,000	15,147,000
London coal-gas.	489,000	17,370,000
Gas used by Grashof	484,500	14,510,000
Gas used by Slaby[1].	466,000	18,500,000
	424,000	16,850,000
Dowson gas (cubic foot at 0° C.) .	125,000	9,000,000

In the Bavarian "Industrie- und Gewerbe- Blatt" for July 1876, there is an account of very carefully made experiments on explosive mixtures by Professor A. Wagner. Using Munich coal-gas he found that whether he employed a glowing platinum wire or a spark from an induction coil he obtained no explosion with a mixture of four volumes of air with one of gas, but that both these means of lighting the mixture produced an explosion in a mixture of five volumes of air and one of gas. Similarly, both with the platinum wire and electric spark he obtained an explosion in a mixture of twelve volumes of air to one of gas, but no explosion in a mixture of thirteen volumes of air to one of gas. With another sample of gas he obtained explosions through wider limits, mixtures of four to

[1] Dr. Slaby's calculation, Appendix IV.

one and fourteen to one both exploding, or rather burning, for he notes that the mixtures near both superior and inferior limits of combustibility burn with a weak flame. Even the mixture of one to eleven burns with only a moderate strength, as he calls it, and with no visible flame. There can be no doubt that if the mixtures were previously heated the limits set by Dr. Wagner would be considerably exceeded.

APPENDIX II.

Examples of Theoretical Indicator Diagrams referred to in the Lecture.

All these examples have been worked on the hypothesis that the constants for the working fluid were the same as for air. Rankine's constants have been used (*vide* Table II., Appendix I.). The difference between the results obtained with these constants, and the results obtained by using constants applying more accurately to the products of combustion, would not be of such magnitude as to alter any of the general conclusions. The various steps in each calculation are recorded in the Table of Results, calculated for 1 lb. of air by the formulas given in the foregoing Appendix.

Example 1. *Cayley Buckett Type.*—Air at 62·6° Fahrenheit, compressed to 27 lbs. per square inch above atmosphere. Temperature then raised at constant pressure to 1000° Fahrenheit by heat from the fuel. The heated air then expanded adiabatically to twice the previous volume, bringing the final pressure nearly down to that of the atmosphere. This example was chosen as being not dissimilar from the conditions of the engines actually made (*vide* Fig. 2).

Example 2. *Cayley Buckett Type.*—Air compressed to 100 lbs. per square inch above atmosphere. Temperature then raised at constant pressure to 1000° Fahrenheit by heat from the fuel. Air then expanded adiabatically to four times the previous volume, bringing the final pressure nearly down, to that of the atmosphere. This example was chosen to show the increase of efficiency due to larger initial compression.

Example 3. *Ordinary Gas-Engine* (*Otto's or Clerk's*).—Explosive mixture admitted at atmospheric pressure, and at the temperature of 62·6° Fahrenheit (17° Centigrade); adiabatically compressed to 40 lbs. above atmosphere. Heat then added at constant volume until temperature is raised to 2799° Fahrenheit (1537° Centigrade), this being considered a limiting temperature by Mr. Clerk. Fluid then expanded adiabatically until its volume is twice that which it had at the beginning of the cycle. These conditions give a diagram closely resembling that of actual gas-engines. The theoretical diagram is like F N C D E (Fig. 3). This diagram is shown to scale in Fig. 13, where it is marked A.

Example 4. *Gas-Engine, higher Compression.*—Explosive mixture admitted at atmospheric pressure, and at temperature 62·6° Fahrenheit, then compressed adiabatically to 80 lbs. per square inch above atmosphere. Heat added by combustion to fluid at constant volume until temperature is raised to 2799° Fahrenheit. Fluid then expanded adiabatically until its volume is twice that which it had at the beginning of the cycle. Theoretical diagram like F N C D E. This example was chosen to show the effect of increasing the initial compression beyond the pressure usually adopted. This diagram is shown to scale in Fig. 13, where it is marked B.

THEORETICAL EFFICIENCY of NINE HEAT-ENGINES

Type		Cayley or Buckett.	
Maximum Pressure above Atmosphere in lbs. per sq. in.		27	100
Nature of Compression		Adiabatic.	Adiabatic.
Reference Number		1°	2°
Volumes of 1 lb. of air in cubic feet	V_f	13·15	13·15
	V_b	6·271	3·056
	V_c, V_n	12·93	4·702
	V_q, V_s	..	..
	V_d	25·87	18·81
Ratio of expansion	$r\begin{cases}c\\d\end{cases}$	2·0	4·0
	$r\begin{cases}q\\d\end{cases}$	..	..
Ratio of compression	$r\begin{cases}f\\b\end{cases}$	2·097	4·303
	$r\begin{cases}f\\n\end{cases}$	..	..
Intensity of pressure in pounds per square foot (absolute)	P_f	2,116	2,116
	P_n, P_s	..	..
	P_b, P_c	6,005	16,516
	P_q	..	..
	P_d	2,263	2,346
Mean intensity of pressure during expansion; pounds per square foot (absolute)	P_{cd}	3,626	5,830
	P_{qd}	..	..
Mean intensity of pressure during compression; pounds per square foot (absolute)	P_{fb}	3,497	5,498
	P_{fn}	..	..
Temperature in degrees Fahrenheit above absolute zero	τ_f	523·8	523·8
	τ_n	..	..
	τ_b	708·4	949·7
	τ_c	1,461	1,461
	τ_s	..	..
	τ_q	..	..
	τ_d	1,101	830
Work in foot-lbs. indicated by several parts of the diagram (Fig. 3) for 1 lb. of air	A C D E H	69,800	120,100
	A B F H	33,870	78,230
	N F G	..	..
	C D E G	..	..
	N S Q D E G	..	..
Heat supplied in foot-lbs.	H	138,300	93,920
Heat restored in foot-lbs.	H_1	..	..
Heat withdrawn in foot-lbs.	$-H_2$	102,200	51,900
	$-H_3$	0	0
Useful work in foot-lbs. per pound of air	U	35,920	41,756
Theoretical efficiency E_t	$\frac{U}{H}$	0·26	0·44
Reference number		1°	2°

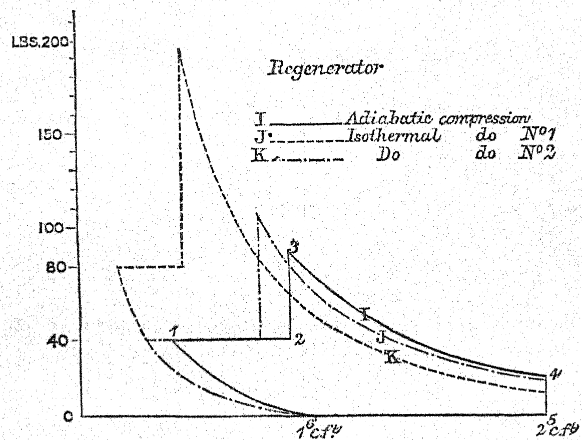
with 1 lb. of Air as working fluid.

Gas-Engine with Compression.				Gas-Engine with Regenerator and Compression.		
40 Adiabatic. 3°	80 Adiabatic. 4°	40 Isothermal. 5°	80 Isothermal. 6°	40 Adiabatic. 7°	40 Isothermal. 8°	80 Isothermal. 9°
13·15	13·15	13·15	13·15	13·15	13·15	13·15
..	..	..	..	..	..	..
5·173	3·502	3·535	2·042	5·173	3·535	2·042
..	..	..	..	11·69	10·07	5·816
26·30	26·30	26·30	26·30	26·30	26·30	26·30
5·084	7·510	7·440	12·88	..	..	..
..	..	..	..	2·250	2·612	4·52
..	..	..	..	..	..	..
2·543	3·755	3·720	6·441	2·543	3·72	6·44
2,116	2,116	2,116	2,116	2,116	2,116	2,116
7,876	13,636	7,876	13,636	7,876	7,876	13,636
33,495	49,480	49,020	84,870	..	..	..
..	..	..	..	14,820	17,210	29,790
3,406	2,907	2,905	2,322	4,733	4,452	3,559
9,748	10,445	10,430	11,280	..	..	..
..	..	..	..	8,188	8,486	9,531
..	..	..	..	..	..	..
3,962	5,062	3,804	4,668	3,962	3,804	4,668
523·8	523·8	523·8	523·8	523·8	523·8	523·8
766·6	898·5	523·8	523·8	766·6	523·8	523·8
..	..	..	..	..	..	..
3,260	3,260	3,260	3,260	..	..	..
..	..	..	..	1,732	1,492	1,492
..	..	..	..	3,260	3,260	3,260
1,685	1,439	1,438	1,149	2,342	2,203	1,761
..	..	..	..	..	..	..
..	..	..	..	..	..	..
14,690	28,400	16,225	28,347	14,690	16,225	28,350
161,200	189,900	189,200	222,000	..	..	..
..	..	..	..	126,200	140,400	195,400
325,300	308,150	357,000	357,000	197,850	230,700	230,700
..	..	..	..	177,600	177,600	177,600
179,400	147,300	147,200	109,600	87,640	69,500	11,840
0	0	36,570	51,855	0	36,570	51,860
146,600	161,500	173,000	193,600	111,600	124,200	167,000
0·45	0·52	0·48	0·54	0·56	0·54	0·72
3°	4°	5°	6°	7°	8°	9°

Example 5. *Gas-Engine with isothermal Compression.*—Explosive mixture admitted at atmospheric pressure, and at temperature 62·6° Fahrenheit, then compressed isothermally to 40 lbs. per square inch above atmosphere. Heat added by combustion to fluid at constant volume until temperature is raised to 2799° Fahrenheit. Fluid then expanded adiabatically until its volume is twice that which it had at the beginning of the cycle. Theoretical diagram like F N C D E, shown to scale in Fig. 14. This example was chosen to show the effect of removing heat from the explosive mixture while it is being compressed.

Example 6. *Gas-Engine with higher Isothermal Compression.*—Explosive mixture admitted at atmospheric pressure, and at temperature 62·6° Fahrenheit, then compressed isothermally to 80 lbs. per square inch above the atmosphere. Heat added by combustion to fluid at constant volume until temperature is raised to 2799° Fahrenheit. Fluid then expanded adiabatically until its volume is twice that which it had at the beginning of the cycle. Theoretical diagram like F N C D E, shown to scale in Fig. 14. This example was chosen to show the effect of increasing the initial compression when this was effected isothermally.

FIG. 20.



Example 7. *Gas-Engine with Regenerator and Adiabatic Compression.*—Explosive mixture admitted at atmospheric pressure, and 62·6° Fahrenheit, then adiabatically compressed to pressure of 40 lbs. per square inch above atmosphere. Passed through a regenerator, from which it receives 177,600 foot-lbs. of heat (per lb. of the mixture) while remaining at constant pressure. Then heated by combustion while at constant volume, until temperature is raised to 2799° Fahrenheit. Fluid then expanded adiabatically until its volume is twice that which it had at the beginning of the cycle, then expelled through the regenerator, to which it gives 177,600 foot-lbs. of heat. Theoretical diagram like F N S Q D E, shown to scale in Fig. 20 where it is marked I. This example was chosen to show the effect of regenerators thus placed.

Example 8. *Gas-Engine with Regenerator and Isothermal Compression.*—Explosive mixture admitted at atmospheric pressure, and temperature 62·6° Fahrenheit, isothermally compressed to a pressure of 40 lbs. per square inch above atmosphere. Passed through a regenerator, from which it receives 177,600 foot-lbs. of heat per lb. while remaining at constant pressure. Then heated by com-

bustion while at constant volume until temperature is raised to 2799° Fahrenheit. Fluid then expanded adiabatically until its volume is twice that which it had at the beginning of the cycle. Then expelled through the regenerator, to which it gives 177,600 foot-lbs. of heat. Theoretical diagram like F N S Q D E, shown to scale in Fig. 20 where it is marked J. This example was chosen to show the effect of isothermal compression when the regenerator is used.

Example 9. *Gas-Engine with Regenerator and higher Isothermal Compression*—Explosive mixture admitted at atmospheric pressure, and temperature 62·6° Fahrenheit. Isothermally compressed to a pressure of 80 lbs. per square inch above atmosphere. Passed through a regenerator, from which it receives 177,600 foot-lbs. of heat per lb. while remaining at constant pressure, then heated by combustion while at constant volume, until temperature is raised to 2799° Fahrenheit. Fluid then expanded until its volume is twice that which it had at the beginning of the cycle. Then expelled through the regenerator, to which it gives 177,600 foot-lbs. of heat. Theoretical diagram like F N S Q D E, shown to scale in Fig. 20 where it is marked K. This example was chosen to show the effect of employing high isothermal compression with a regenerator.

General Remarks on the above Examples.—If the calculations were absolutely accurate, we ought to find the sum of H_2, H_3 and U equal to H. H_2 is the heat rejected in the discharged gases, and H_3 is the heat withdrawn during compression. The same limiting temperature was adopted for all the examples of explosive engines, because the maximum average temperature of the fluid after combustion seems nearly the same in actual engines by various makers. The high efficiency of Example 9 as compared with that of Examples 7 and 8 is due to the fact that the heat rejected in the products of combustion is comparatively small. It would have been possible by trial to find exactly the maximum quantity which on each hypothesis could be stored and restored so as to make $H_2 = 0$. If this had been done, the efficiencies of 7, 8, and 9 would all have been higher, but the efficiencies of 7 and 8 would have been increased much more than that of 9. This warning is given to guard against the supposition that there is any marked superiority in isothermal compression. In working other theoretical examples with a regenerator, it must be remembered that the fluid cannot be raised by the regenerator above the temperature to which it is reduced by expansion in the cylinder, in other words τ_s must be less than τ_d.

APPENDIX III.

Description of Engines referred to in the Lecture.

1st. Otto's Gas-Engine, as made by Messrs. Crossley.

Fig. 4, Plate 2, shows a sectional plan of Otto's engine, as made by Messrs. Crossley Bros., of Manchester.

A is the gas-cylinder, in which a deep piston L works connected to a crank by a connecting-rod. The cylinder is open to the air at what I will call the far end. A water-jacket, M, surrounds the cylinder, and water is continually supplied cold to this jacket, and withdrawn warmed by heat which has passed through the metal walls of the cylinder. The heat thus withdrawn (about one-half of all that is produced) is absolutely wasted as regards the production of work. This waste is necessary, in order to keep the temperature of the inner surface of the cylinder low enough to permit lubrication. An explosive mixture of gas and air is admitted by C, being drawn in by L during

FIG. 21.

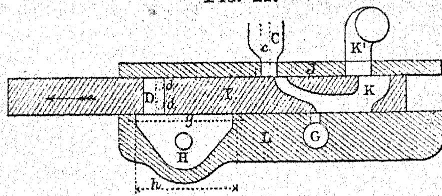


FIG. 22.

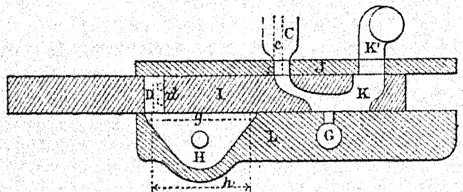


FIG. 23.

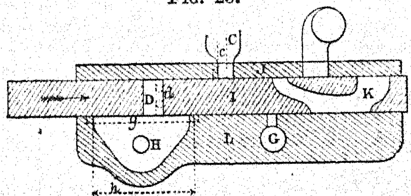


FIG. 24.

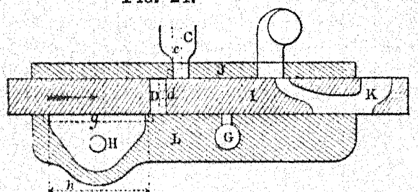


FIG. 25.

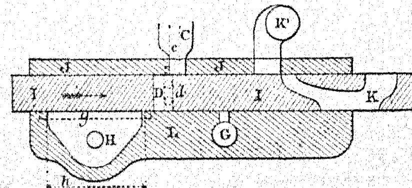
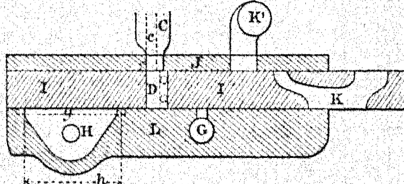


FIG. 26.



stroke one of each cycle (forward, *i.e.*, from the near to the far end of the cylinder). During stroke two (backward) this fluid is compressed by the piston L; when stroke three (forward) begins the mixture is fired and performs work. During stroke four (backward) the products of combustion are expelled by the exhaust-pipe E; the piston does not, however, go quite home, so that these products are not wholly expelled, and during the next stroke they are said to form a sort of cushion between the incoming explosive mixture and the piston, or these products of combustion may be used to mix with the incoming fluid, and retard combustion. Messrs. Crossley attach much importance to the action of this residual charge of burnt gas and air.

In the cycle of four strokes the first might be called the charging-stroke, the second the compression-stroke, the third the working-stroke, and the fourth the discharge-stroke.

The action of the valves can be best understood by reference to the six figures 21 to 26. J is the cylinder face, through which the port C leads into the cylinder; K^1 is the passage through which air is drawn for the explosive mixture; I is the slide-valve, in which passage K is formed to admit both gas and air; also the small port D by which the mixture is fired. The slide-valve works between the cylinder face and a fixed cover L. The gas is supplied through a passage G in this cover, which also contains a chimney or opening, H, inside which a small gas-jet, called the slide-light, is continually burning. H is open to the air above and below; a groove *g* is seen dotted below H. This groove is formed in the cover, and is not open to H, but receives gas by an independent pipe; it is open on the side next the slide, and is closed by the slide, except when the lighting port D comes opposite to it; then D is supplied with gas by the groove *g*.

There is another opening *c* from the cylinder to the cylinder face, which I will call the equilibrium lighting port, and level with this port there is a passage *d* in the slide-valve, which leads to the lighting port D by two holes shown. The exhaust-valve is separately worked, and is not shown.

Fig. 21 shows the slide-valve I travelling in the direction of the arrow at the beginning of the charging-stroke of the piston; air is coming from K^1 into K, where it mixes with gas coming from G. The mixture is passing on through the other end of the passage K to the cylinder through C; the lighting port D is receiving gas from the groove *g*, and this is burning in connection with the flame in the chimney H. As the charging-stroke proceeds, the slide-valve reaches the limiting position shown in Fig. 22 when the admission-valve is wide open.

Fig. 23 shows the position of the slide-valve when the piston has travelled about half way back during the second or compression-stroke. The slide is moving in the direction of the arrow; both air and gas are cut off from the passage K; gas is still supplied to the lighting port D from the groove *g*, and this supply is still burning in connection with H.

Fig. 24 shows the position of the slide when the compression-stroke is nearly ended. The supply of gas to the lighting port D is just about to be cut off, and the lighting port D is just about to be placed in communication with the cylinder by the opening *c*; the two events will happen simultaneously. The lighted gas in D will receive an accession of explosive mixture from *c*, serving both to maintain combustion and to bring the pressure in D up to that in C before the position shown in Fig. 25 is reached. In Fig. 25 the slide-valve has advanced a little further; the working-stroke is just beginning. The lighting port D is in connection with C; the explosive mixture, which has been supplied through *d*, is now well lighted, and expands, shooting a tongue of flame out through C,

and firing the mixture in the cylinder for the working stroke. It will be seen that the exploding mixture is completely shut in by the valve. Fig. 26 shows the extreme position reached by the slide I during the working stroke. After this it returns to the position shown in Fig. 21. During the return the cylinder is closed by the slide I; the gas in D is extinct, or D is filled with products of combustion, which will gradually be expelled by incoming gas from g, as the slide returns towards the first position. When these products are sufficiently expelled, the new supply of gas to D will be lighted at H. It will be noted that the valve travels only once back and forth during the four strokes of the engine. The supply of gas to G is under the control of a governor acting on a separate valve.

Fifteen thousand Otto engines have been sold; seven thousand of which have been made by Messrs. Crossley Bros., to whom the introduction of this engine in Great Britain is due. The practical and mercantile success of gas-engines may be said to have been established by the Otto engine.

This success I believe to have been due to four features:—1. The initial compression. 2. The good lighting-gear above described. 3. Control over the rate of combustion, obtained by using the residual products of combustion as a diluent for part of the incoming charge. A strong mixture is ignited, and a weaker mixture burned for the rest of the stroke. 4. The simplicity of construction obtained by using one cylinder and piston alternately as a pump and a motor.

Full details are given of the trial of a 4 HP. engine in Appendix IV.

Messrs. Crossley have supplied the following additional information. Their latest type is what is termed a twin-engine, in which two precisely similar engines are coupled, so that the working-stroke of one corresponds with the charging-stroke of the other. Both connecting-rods work on one crank. The speed varies only from one hundred and fifty-five revolutions per minute to one hundred and sixty revolutions when running half loaded and quite light. One of these engines, rated at 12 HP., stands in a space 10 feet 3 inches by 4 feet 8 inches, indicates 28 HP., and gives 23 HP. on the brake; consumption, when running light, 100 cubic feet of Manchester gas; at full load, 560 cubic feet, or about 20 cubic feet per HP. per hour.

The following Table gives particulars for various sizes of the ordinary single engine:—

Nominal Horse-power.	Approximate Indicated Horse-power.	Approximate Net Weight of Engine.			Approximate Weight packed complete.			Standard Sizes of Pulleys.	
		Cwt.	q.	lbs.	Cwt.	q.	lbs.	Diam.	Wide.
½	1·9	12	0	0	16	0	0	10 ×	5
1	2·7	17	0	0	21	0	0	12 ×	6
2	3·96	26	0	0	30	2	0	17 ×	6
3½	5·9	32	2	0	37	0	0	20 ×	7
6	11·57	52	0	0	60	0	0	24 ×	10
8	14·7	54	2	0	62	0	0	27 ×	12
12	24	74	0	0	84	0	0	36 ×	12
16	40	131	0	0	143	2	0	54 ×	18

The speed of all sizes is one hundred and sixty revolutions per minute, except 1 HP. and ½ HP., which run at one hundred and eighty.

2nd. *Mr. Dugald Clerk's* engine, as made by Messrs. Thomson, Sterne, and Co., is shown in Figs. 5 and 5A.

A represents the working cylinder, open at the far end, and having a deep piston, C, connected to a crank by a connecting-rod as in ordinary trunk-engines. The cylinder is surrounded by the usual water-jacket N; the explosive mixture is admitted by a self-acting valve V from a displacement cylinder B, in which a second piston D is worked from the main driving-shaft. The explosive mixture, entering at F, fills and passes through a conical clearance space G, before reaching the working cylinder A. The exhaust or discharge openings are at E E round the cylinder at the far end, and lead to a discharge-pipe E_1. There is no exhaust valve; the exhaust openings are closed by the piston C, when that is in the front or near part of the cylinder, and they are uncovered or opened by the piston when near the far end of its stroke. The explosive mixture is fired by a slide-valve with a lighting port of the same general character as that already described for the Otto engine. A flame burns continually in the chimney H; a lighting port *h* receives an explosive mixture, which is lighted by H, blows a part of the flame into the open air (unlike Otto's here), and is then carried on to the opening *f*, through which it fires the mixture in G. There is a special adjustment by which the charge given to *h* is regulated.

The slide-valve I has another port M for the main supply of gas derived from the pipe K. The port M allows the gas to pass through a pipe L into the chamber below the self-acting or spring-valve V, and over the similar valve W, separating the valve-chamber from a receptacle P into which air is drawn through the india-rubber flap-valve Q. The valve-chamber between V and W is in direct communication with the cylinder B. The proportion in which gas and air are mixed to form the combustible mixture is regulated by the slide-valve I, which cuts off the gas at a certain point in the stroke.

The engine acts as follows:—When the parts are in the position shown the forward stroke has just been completed, and the exhaust E is open; C is almost stationary or moving slowly back, driving out some of the products of combustion through E; the piston D, which has considerable lead relative to C, is moving quickly back, driving before it the explosive mixture which passes from B, through O between W and V, up through V into G, displacing the products of combustion formed during the preceding stroke, and expelling those through E E. This action continues until just before the piston C closes the exhaust. The whole of the burnt charge has been expelled and a portion of the newly introduced charge has begun to pass out through the exhaust: in order that this may entail no waste, the charge previously drawn in by B towards the end of its forward stroke is pure air, gas being excluded by the slide-valve, consequently the first portion of each new charge delivered into the working cylinder is pure or nearly pure air, and this may be allowed to follow the products of combustion out by the exhaust with no loss of gas. The exhaust is now closed as piston C advances on the return stroke; the piston D begins its upward stroke and valve V is closed by its spring. The explosive mixture in A and G is compressed by C until it occupies only the conical part of the chamber G; meanwhile B has been drawing in air through valve Q, valve W, and pipe O. This air has received gas from the port M, which has been mixed with the air by the baffle-plate at the entrance to B. Towards the end of the stroke of D, the slide-valve I cuts off the supply of gas, so that air alone is admitted to O. When C has passed the end of its back stroke, and begins to move forward, the slide-valve I fires the charge through *f*; the working stroke is then performed; the valve V is held closed by the pressure in G as well as by its spring. The forward stroke of piston D is completed, while the piston C is moving forward rapidly near the middle of its stroke; shortly before this the valve I has cut off the supply of gas by the port M, so that the last part of the charge drawn in by D was pure air; piston D now

begins to compress the charge a little, but this does not open the valve V, as the pressure on the other side is much greater. Near the end of the forward stroke of C the exhaust is uncovered; the exhaust products begin to flow out, the valve V opens, and the substitution of a fresh charge for the old burnt charge begins.

About 500 of these engines have been made by Messrs. Thomson, Sterne and Co. They share with the Otto engine the merit of initial compression and a good firing gear; the rate of combustion admits of being controlled by the novel and ingenious method of admission and discharge, which allows a rich mixture to be supplied for firing near one end of the cylinder and a poor mixture for gradual combustion at the other. There are more parts than in the single Otto engine; but there is one working stroke in two instead of one in four.

Mr. Dugald Clerk has supplied the following particulars of the performance of an engine rated at 6 HP.:—Diam. of piston, 7 inches; stroke, 12 inches. Speed of engine, one hundred and sixty revolutions per minute; available average pressure, 55·8 lbs. per square inch; indicated horse-power, 9·76; brake horse-power, 7·7; maximum pressure, 206 lbs. per square inch; pressure of compression, 61 lbs.; consumption of gas per I.HP. per hour, 20·6 cubic feet; consumption of gas per brake HP. per hour, 26·3 cubic feet. The resistance of the gases in the displacement cylinder gives rise to an indicator diagram corresponding to about 0·56 HP., so that the friction of the mechanical parts is about 1·5 HP. With a 12-HP. engine the consumption per I.HP. was 17 cubic feet per hour, and per brake HP., 24·12 cubic feet.

The following experiment (29th August, 1883), with an 8-HP. engine, may be compared with that made by Dr. Slaby on an Otto engine. A measured amount of water was run through the jacket, the temperature of the water observed by thermometers at the inlet and outlet. The engine was allowed to run for some time with a full load; speed, brake power, indicated power, and gas supplied were measured at intervals. When the temperatures of the thermometers were steady Mr. Clerk found that 972 lbs. of water were passed through per hour with an average rise of temperature of 67° Centigrade. This loss of heat did not include that from the frame, which was considerable, as the temperature of the upper part was 84°. 330 cubic feet of gas were used per hour, and the average indicated power was 17·7. Taking 505,000 foot-lbs. as the heating value of Glasgow coal-gas, the total heat given to the engine was 166,650,000 foot-lbs.; the heat carried away by the water was 90,522,360 foot-lbs., or 54 per cent. of the whole heat supplied by the gas.

3rd. The *Buckett* engine (Fig. 1, Plate 2) has been very fully described in the body of the lecture. The sizes made up to the present date range from $\frac{1}{4}$ to 12 horse-power. Thirty or forty engines have been supplied to the public. The data and diagram given (Fig. 2, p. 5), were taken from a 12 nominal HP. double-cylinder vertical engine; 41·24 gross HP. were indicated in the working cylinder; 21·04 HP. were indicated in the pumps; leaving 20·2 HP. as the net result from the two cylinders; 14·39 HP. was done on the brake, giving a mechanical efficiency of 0·71. Air was drawn from the stokehole at nearly 100° Fahrenheit; the products of combustion were admitted to the cylinder at from 1400° to 900° Fahrenheit. The temperature of the discharged gases varied from 500° to 900°. These temperatures were determined by Mr. Charles Ingrey, of the Caloric Engine Company. Diameter of working cylinders, 24 inches; diameter of pumps, 18 inches; stroke of working piston and pumps, 16 inches; speed, 61 revolutions per minute; weight, 6 tons 6 cwt.; base-plate, 6 feet 3$\frac{1}{4}$ inches × 5 feet 4$\frac{3}{4}$ inches; height, 8 feet 3 inches; width and length of whole engine, 7 feet 4 inches × 7 feet. Stoking required at intervals of about 20 minutes—fuel, gas coke—11 to 12 lbs. in each charge. The consumption of coke was 1·8 lb. per hour per I.HP.

and 2·54 lbs. per hour per brake HP; mean pressure on pistons, 18·5 lbs. per square inch; mean pressure in pumps, 16·78 lbs. per square inch. Price £320.

A one-horse engine weighs 1 ton 1 cwt., is contained in a space 4 feet 5 inches × 3 feet × 3 feet 8 inches, and costs £110.

4th. Messrs. A. E. and H. Robinson's hot-air engine is shown in Fig. 16, Plate 2, as made by Frank Pearn and Co., of Manchester. It is a true Stirling engine, having the working piston C attached by one connecting-rod D to one crank E on the working shaft, while the regenerator F is attached by a rod working through C to a second connecting-rod, and a second crank at right angles to the first. The upper part of the cylinder is cooled by a water-jacket A_2, but the lower portion of the cylinder is lined by non-conducting material at A_3. The cylinder is closed at the bottom by a dome-shaped plate B, and at the top by the piston C. Heat is supplied by a Bunsen burner at H, and the products of combustion are deflected by a baffle-plate leading into the chimney G. This chimney has a casing G_1, through which the air for combustion is drawn into the space G_2 to supply the burner. A tap and governor permit some regulation of the internal pressure, but there is no compressing pump to supply leakage, so that the maximum internal pressure can never be large, which is a disadvantage.

The engine acts as follows:—When the regenerator F, which is also a displacer, is at the bottom of the stroke, the mass of air is contained in the chamber between C and F, and in the clearance of the wire-gauze regenerator. The bulk of the air has therefore been cooled by passing up through the regenerator, and is, moreover, losing heat to the water-jacket. The air consequently contracts, and the piston C descends; as it nears the bottom of its stroke the regenerator begins to rise, and when C reaches the bottom the regenerator rises fast. The air, passing through the wire-gauze, regains the heat it had previously lost, and expands, beginning to raise the piston C. As the regenerator rises still further, the bulk of the air passes into the space between F and the dome-plate B, from which it receives heat, causing it to expand still further. The regenerator F remains near the top position until C has completed the greater part of its stroke, when it begins to descend. In fact, the working depends on the alternate heating and cooling of one and the same mass of air. This heating and cooling is in the main effected by the regenerator, but at each stroke some heat is supplied by the fire, and some taken away by the refrigerator. Heat is therefore supplied only when the fluid is at the highest temperature, and withdrawn only when the fluid is at the lowest temperature. This being the condition required for a perfect heat-engine, the whole action of the engine would be reversible if the sides of the chamber were non-conducting and if the regenerator acted perfectly, but a certain leakage of heat up the regenerator must always occur with such engines. It should be noted that the working piston is cool.

Messrs. Robinson supply engines according to the following Table:—

Power.	Price.	Revolutions per Minute.	Diameter of Pulleys.	Approximate Cost of Gas Per Hour.	Diameter of Piston.	Stroke.
	£.		Inches.	*d.*	Inches.	Inches.
One-man	25	270	5	$\frac{1}{2}$	6	5
One-and-a-half-man .	30	270	7	$\frac{3}{4}$	..	..
Two-man	35	270	9	$\frac{7}{8}$	8	5

They take 4,000 foot-lbs. per hour as the rate of work which they call one-man power.

5th. Messrs. W. H. Bailey and Co., Salford, Manchester, make a hot-air engine, of which one type is shown in Fig. 17, Plate 2. It consists of a cylinder D, closed at one end by a steel pot G, and at the other by a piston H, attached to the crank-shaft by a series of levers. A separate crank, at right angles to the main crank, works the displacer E by a piston-rod passing through the front or working piston. The furnace is at K_1, and delivers the products of combustion, as shown by the arrows, into the space K_2, round the steel pot, and out by K_3. Heat, therefore, is supplied to the air when in the space B, between the displacer E and the pot G. There is a water-jacket round the other end of D, by which heat is withdrawn from the air when in the space C. The working air passes backwards and forwards between C and B, through the narrow passage left between D and E. The metal walls of this passage play the part of a regenerator, serving to cool air when it is passing from B to C, and to restore heat to it when passing from C to B. This engine is therefore a true Stirling engine, working without valves or exhaust, and, like Robinson's, with no compressing pump to enable it to work at high pressure. The description given of the action of Robinson's applies exactly to Bailey's engine, which is, however, made of larger sizes, and is adapted for heavier work. These engines have a small valve, by which air is

Fig. 27.

Bailey Engine.

introduced whenever the internal pressure falls below that of the atmosphere. The indicator-diagram is shown in Fig. 27. This diagram was taken from an engine nominally of 1 HP., having a piston with $6\frac{3}{8}$ in. stroke, and $14\frac{5}{8}$ in. diameter. The diagram is one of a set, the average of which gives 2·37 HP. at a speed of one hundred and six revolutions per minute. The estimated temperature was 373° Centigrade at the atmospheric pressure, and 823° Centigrade at the highest pressure. The brake-power of this engine was 1·31, giving a mechanical efficiency of 0·55. The highest pressure was nearly 14·7 lbs. per square inch above the atmosphere. The consumption of coal is said to be under 10 lbs. of common coal per hour, and the quantity of cooling water 30 gallons per hour. The makers claim that, in comparison with gas- or steam-engines, less expense is incurred in oil and attendance; also that the engine lasts a longer time. They refer for the theory of these engines, of which they make more than one type, to a Paper by Dr. Slaby in the "Verhandlungen des Vereins zur Beförderung des Gewerbfleisses," December 1878, and to a Paper by Gustav Schmidt in "Dingler's Polytechniches Journal," vol. clx., part 6, 1861. Messrs. Bailey deserve credit for introducing this type of engine to the English market, but it is to be regretted that they should call the engines by the names of the foreign designers, Lehmann and Laubereau, rather than by the name of Stirling, which should be used for all these engines. Neither Lehmann nor Laubereau have introduced features which

Stirling did not describe. On the contrary, the omission of a distinct regenerator is a defect which Messrs. Bailey would do well to remedy. Stirling made larger engines, and obtained a higher HP. per lb. of coal than Messrs. Bailey claim. These remarks are not intended to throw discredit on the foreign inventors, or on Messrs. Bailey. On the contrary, they are intended to show that there is room for practical improvement, and they are prompted by the conviction that it would be possible, by increasing the heating-surface and raising the pressure inside the cylinders, to reduce the consumption of coal below that of first-class steam-engines. The theory of the engine is sufficiently explained in Rankine's Treatise on the Steam-engine.

The second type of Bailey's hot-air engine is almost identical with the woodcut in Rankine's book, with the omission of the regenerator—a decidedly retrograde step.

The following Table gives the sizes of engine made by Messrs. Bailey :—

Horse power	$\frac{1}{4}$ to $\frac{1}{3}$	$\frac{1}{2}$ to $\frac{2}{3}$	$\frac{3}{4}$ to 1	1 to $1\frac{1}{2}$	$1\frac{1}{2}$ to 2	2 to $2\frac{1}{2}$	3 to $3\frac{1}{2}$
Price of engine, including governors	£. 35	£. 40	£. 60	£. 75	£. 100	£. 125	£. 150
Packing	30/	35/	45/	53/	70/	90/	150/
Revolutions per minute	120	100	100	100	90	90	80
Diameter of pulley	Inch. 9	Inch. 12	Inch. 16	Inch. 18	Inch. 21	Inch. 24	Inch. 30
Weight with stove fittings, approximate	Cwt. 9	Cwt. 12	Cwt. 17	Cwt. 20	Cwt. 32	Cwt. 50	Cwt. 63
Length of engine	Ft. In. 6 10	Ft. In. 8 0	Ft. In. 9 0	Ft. In. 9 9	Ft. In. 11 6	Ft. In 12 9	Ft. In. 15 6
Breadth of engine	2 0	3 6	3 8	3 8	3 11	4 4	4 8
Height of engine	3 4	4 0	4 6	4 10	5 0	5 8	5 9

This type of engine is largely employed in Germany.

6th. Rider's hot-air engine, an American design, introduced into this country by Messrs. Hayward and Tyler, has many points of similarity with the Stirling engine, but is not identical with it. This engine, shown in Fig. 18, Plate 2, consists of two cylinders, A and B, both open at the top, and containing two pumps, C and D, connected by cranks nearly at right angles, as in the Stirling engine. The fire acts against the bottom of the cylinder B; a cooling water-jacket E surrounds cylinder A. The two cylinders are joined by a passage H, containing a regenerator. In the position shown C is at the bottom, and D is about one-third of the way along its stroke; the mass of working air, which is not changed, is compressed, and is almost all in the hot chamber above F receiving heat. It consequently expands, and lifts the plunger D. The plunger C begins to rise slowly at the same time, assisted by the pressure beneath it. When the plunger D has reached the top of its stroke, the plunger C is more than half way up, and the air is thus rushing rapidly from the cylinder B through the regenerator into E; it is being cooled first by the regenerator, where heat is stored, and then by the water-jacket, where heat is finally withdrawn. The plunger D now descends, completing the transfer of the air to the cold cylinder A through the

regenerator. The pressure falls during the downward stroke of D, in consequence of the cooling of the air. When D is about one-third down, C begins to descend, and the air is thus compressed while chiefly in the cold cylinder. While being compressed it is at its lowest temperature, and is being cooled. The air is next transferred from the cold cylinder to the hot one by the last part of the downward stroke of C, and the first part of the upward stroke of D. The bulk is little changed during this period, but the pressure rises considerably. The following is the cycle of changes which occur to the mass of working air:—

1. A small bulk of cold air has heat restored to it by the regenerator, the pressure rises during this process; the back pressure on C counterbalances the forward pressure on D. This is a period of displacement.

2. The small bulk of air receives a fresh supply of heat at the highest temperature, expands doing useful work by pressure on D, and subsequently on C to a less extent.

3. A large bulk of air is transferred from B to A, and its heat taken away from it, being stored in the regenerator. The pressure falls. The forward pressure on C during the last half of its upward stroke counterbalances the back pressure on D. This is a period of displacement.

4. The large bulk of cold air is compressed into small space by C. The back pressure against C is not counterbalanced by the forward pressure on D. Hence during this period work is required from the flywheel to compress the air, but at the same time heat is withdrawn while the fluid is at the lowest temperature; and the work required to compress the fluid while cold and losing heat, in the fourth period, is considerably less than the work given out by the fluid while expanding when hot and receiving heat in the second period.

The working power of the engine is the difference between the work done in the second period and that required in the fourth. The cycle of changes described is not quite identical with the Stirling cycle. In the Stirling engine the compression is wholly effected by the working piston; the second plunger is a mere displacer, which never exerts any back pressure. The pure Stirling type seems to me superior in every respect to this variety. The working piston in the Rider engine is hot, instead of cold, as in Stirling's make, and the indirect action of compression though the crank-shaft of Rider's introduces extra strains, requiring heavier parts, and causing more friction than Stirling's design. The engines made by Messrs. Hayward and Tyler are rated as $\frac{1}{4}$, $\frac{1}{2}$, and 1 HP., and are chiefly used for domestic water-supply. They run at a speed of from one hundred to one hundred and forty revolutions per minute, and a pressure-gauge on them registers 20 lbs. as a maximum pressure above the atmosphere.

The 1 HP. engine has plungers 10 inches in diameter, and a stroke of 13 inches. It stands on a floor-space 4 feet 4 inches by 2 feet 8 inches, and the height to the top of the flywheel is 7 feet 6 inches. The weight of the engine and flywheel is 28 cwt. 2 qrs. 14 lbs. It is claimed that this engine will pump 1,200 gallons per hour 80 feet high for 9 lbs. of coke. This is equivalent to about $\frac{1}{2}$ useful HP., or about 18 lbs. of coke per HP. per hour.

The $\frac{1}{4}$ HP. engine does an effective work in pumping of about 0·1 HP., and the consumption of coke is about 25 lbs. per effective HP.

These consumptions of coke may seem large per HP., but considering the size of the engine, they are really very moderate. The price of the 1 HP. engine is £86, and that of the $\frac{1}{4}$ HP. £41.

In conclusion, it is much to be regretted that English makers should import imperfect foreign types of hot-air engines, when a much better description of engine has been made by our own countryman, and very carefully described in

his patents. It is probable that for small sizes his compressing pump might be omitted, in order to simplify the construction. If this were done, and his directions followed, a better hot-air engine would be produced than is now in the market. A little trouble would be required to fix exactly the best proportions of the air-spaces and the best size of regenerator; but if the inferior types find a sale, it would surely pay any maker to incur the small necessary outlay, under the advice of some engineer who has made a study of caloric-engines.

APPENDIX IV.

Comparison of the Lenoir and Otto Gas Motors, by Dr. A. Slaby.

The following report was written by Dr. A. Slaby, Professor in the Royal Technical High School, Berlin, with the object of sustaining Otto's patent in the trial Otto *v.* Linford. It was forwarded to Professor Jenkin by Messrs. Crossley, and is published with their consent. A few passages, referring rather to the legal than to the scientific aspect of the question, have been omitted. The account of the experiments is remarkably complete, and the only part of the analysis of the performance which seems open to question is the calculation of the constant m, the value of which is determined on the assumption that in each change of pressure and volume pv^m will be constant. This assumption cannot be granted as even approximately true for those parts of the cycle where combustion is taking place. After referring to an experiment on Lenoir's engine made by Tresca, and published in the "Annales du Conservatoire," vol. i., p. 849, Dr. Slaby continues:—

In both engines a mixture of air and inflammable gas is fired in a cylinder producing explosion and subsequent expansion. The expansion curve produced in either case is of the greatest consequence. It is well known that expansion curves, that is to say, curves having their abscissæ representing volumes and their ordinates representing pressures, can be approximated to by curves of hyperbolic character, having the co-ordinate axes asymptotes to them. Generally these curves can be referred to equations of the form pv^m = constant, in which p and v are the variable pressure and volume, and m is a constant which is different for each different curve. As to the possible curves resulting from variation of m, two cases are especially to be remarked.

1. When $m = 1$, the equation pv = constant is that of a rectangular hyperbola, the isothermic curve of expansion according to Boyle's law. According to this curve a gas expands under constant temperature. As such expansion produces work, and as, according to the law of thermodynamics, work can only be obtained at the cost of heat, it is necessary, in order to have an expansion of this kind, to supply the gas with continual additions of heat during its expansion. This heat is immediately and completely converted into mechanical work, the expanding gas losing no part of its original heat.

2. A second case of expansion curve worthy of remark is that in which the ratio of specific heat under constant pressure to that under constant volume (a ratio usually[1] indicated by the symbol k) is taken into account. The value of this ratio for air and for the gases dealt with can be ascertained.

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[1] Dr. Slaby's notation is retained throughout this Appendix. The symbol k corresponds to γ in Appendix I.

The expansion curve having the equation $pv^k =$ constant is called, as proposed by Rankine, "adiabatic," representing expansion of a gas when heat is neither supplied to it nor abstracted from it by extraneous bodies.

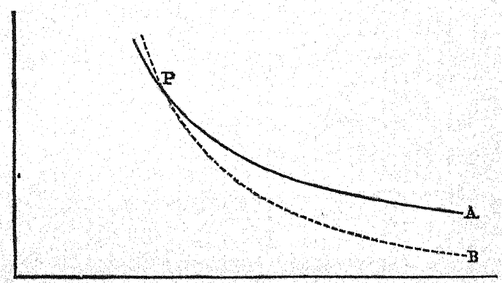
As in this case the performance of work by expansion must be accompanied by expenditure of heat, this heat can only be derived from the expanding gas itself, and consequently its temperature is reduced as it expands.

In the annexed diagram (Fig. 28), the adiabatic curve B has the same character as the isothermic curve A, but its ordinates decrease more rapidly.

From a given starting-point P both curves can be drawn, the constant k being known.

All expansion curves drawn through P, when $m < 1$, lie above A. They would represent expansions under continual supply of heat to make up for the expenditure in the shape of mechanical work, and to raise the temperature of the expanding fluid. It is a peculiarity of such curves that the heat supplied must exceed that which is due to the work performed, so that the temperature of the fluid is continuously elevated.

FIG. 28.

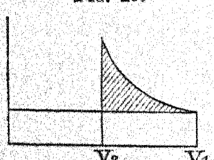


All expansion curves where $m > k$ lie under B. They represent expansions under continual abstraction of heat by contact of the expanding fluid with colder bodies. In such a case, as part of the heat goes to performance of work and part is abstracted, the temperature of the fluid falls more rapidly than in adiabatic expansion.

Between the two curves A and B obviously lie those for which $m > 1$ and $< k$.

For these there is necessarily a supply of heat, though not so much as is equivalent to the work performed by expansion. This work is therefore due partly to heat given out by the fluid itself, partly to that extraneously supplied. The more nearly the curve approaches A, the greater is the heat supply; the more nearly it approaches B the less is the heat supply.

FIG. 29.



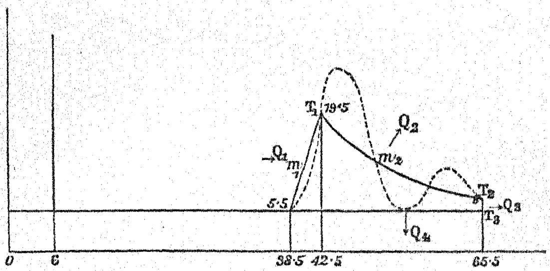
Turning now to Lenoir's engine, we can, on the principles stated, determine the action of the heat when we know the nature of the expansion-curve. The general arrangement of the engine is as follows:—While the piston performs the first half of its stroke, a mixture of air and gas is drawn into the cylinder through openings governed by a slide, and at the middle of the stroke the mixture is exploded. The diagram, therefore, shows in its first half a parallel line at atmospheric pressure, and when the volume is as indicated at v_2, at which point the ignition takes place, the pressure ordinate rises suddenly to its maximum. As the piston continues its

stroke to the end, the products of the explosion expand in their proper curve, and during the return stroke they are discharged at atmospheric pressure. The shaded portion of the diagram, therefore, represents the indicated work.*

The nature of the expansion-curve is of great interest. Tresca, on p. 862 of his Paper, gives a diagram taken from a Lenoir engine. An exact copy is shown by the dotted line on the annexed Fig. 30. Eliminating the oscillations of the indicator spring, by drawing the full line, and determining the co-ordinate axes with an allowance for clearance spaces of 10 per cent. of the whole capacity of the cylinder, we get a diagram the curve of which has the equation $pv^2 =$ constant.

As the value of k for expanding gases is 1·38, it follows that in this case, where $m = 2$, the expansion-curve must lie below the curve B previously discussed, consequently there must be during the expansion an abstraction of heat by the water-casing of the cylinder.

FIG. 30.



According to Tresca's statement, the heat abstracted by the cooling water amounts to 66 per cent. of the total produced by the combustion of the gas, whilst only 4 per cent. is converted into useful work, the remaining 30 per cent. being partly absorbed by the discharged products of combustion, and partly lost in shocks and friction. This loss of more than 30 per cent. of the heat of expansion shows clearly the principal defect of the engine. By the sudden combustion of the gaseous mixture an extremely high temperature is produced, and a blow, which owing to the rapid fall of temperature quickly passes, is given, destructive of the working parts of the engine.

The unsatisfactory result of the Lenoir engine led to many efforts to improve the working of gas engines. The chief defect lay in the use of a too strongly explosive mixture.

After Tresca's experiments Lenoir employed a homogeneous mixture consisting of 12·6 volumes of air to 1 of gas. Greater dilution of the gas was tried, but failed for a simple reason. Ordinary illuminating gas requires for its complete combustion 6·3 volumes of air to 1 volume of gas. By very careful experiments Wagner found (see Bayr. Gewerbeblatt, 1876, p. 184) that certain ignition by red-hot platinum, or by an electric spark, begins at a proportion of mixture 1 to 5, but when the proportion attains 1 to 13 it entirely ceases to be possible. Lenoir by employing the proportion 1 to 12·6 approached closely the limits of combustibility, and consequently the way to employ a more dilute uniform mixture was completely closed against him. It was not possible to work the engine with a gas supply less than 2·7 cubic metres per horse-power per hour continuously.

*

No greater success attended the efforts of those who between 1861 and 1876 endeavoured to improve the gas-engine. During this period more than one hundred patents for gas-engines were taken in America, England, France, and Germany. In most of these engines the consumption of gas exceeded that in Lenoir's. One of these engines (Weyhe's) was found on trial to consume 3 to 4 cubic metres, and another (Bisschop's) 5 to 6 cubic metres per horse-power per hour. Thus the Lenoir engine proved to be the best of those engines that worked with a homogeneous mixture of gas and air.

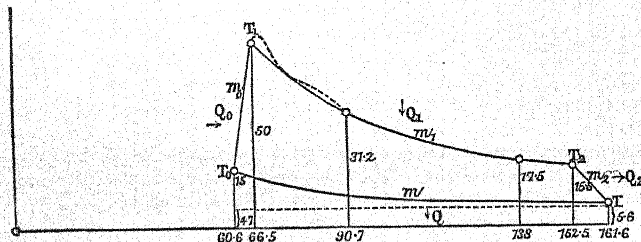
This was the position of the gas-motor engine in 1876.

The essence of Otto's invention consists in a definite arrangement of the explosive gaseous mixture, in conjunction with inert gas, so as to suppress explosion [and nevertheless ensure ignition].

At the touch-hole, where the igniting flame is applied, lies a strong combustible mixture which ignites with certainty. The flame of this strong charge enters the cylinder like a shot, and during the advance of the piston it effects the combustion of the farther layers of dispersed gaseous mixture, whilst the shock is deadened by the cushion of inert gases interposed between the combustible charge and the piston.

The complete action takes place in a cycle of four piston strokes. The first serves for drawing in the gases in their proper arrangement and mixture; the

Fig. 31.



second compresses the charge; during the third the gases are ignited and expand; and, finally, by the fourth the products of combustion are expelled. The essential part of the working is performed by the first of these strokes, by which the charge is drawn in and arranged, first air, then dilute combustible mixture, and finally strong combustible mixture.

This arrangement is obtained by the working of the admission slide. Moreover, after discharge of the products of combustion, a portion remains in the clearance space of the cylinder, and this constitutes the inert layer next the piston. By this peculiar arrangement of the gases, the ignition and combustion above described are rendered possible, whilst the products of previous combustion form a cushion, saving the piston from the shock of the explosion of the strongly combustible mixture at the farther end of the cylinder.

In the expansion diagram (Fig. 31) the charging stroke is indicated by the dotted parallel line at atmospheric pressure. The compression effected by the return stroke is indicated by the curve $T\,T_0$. The sudden expansion resulting from the explosion of the strong gaseous mixture is shown by the steeply rising line $T_0\,T_1$, and the expansion during the rest of the stroke by the curve $T_1\,T_2$. The discharge valve opening a little before the end of the stroke, the line

descends more rapidly from T_2 to T. During the discharge stroke the back pressure is nearly constant, and is indicated by the dotted line at atmospheric pressure. Thus for every four piston strokes the power diagram is that contained within the full lines.[1]

Briefly it may be stated that a certain quantity of fluid compressed from T to T_0 is, by a large addition of heat, increased to the pressure T_1, while the piston already performs a portion of its stroke; with further additions of heat to the fluid, this expands to T_2, until, by a sudden withdrawal of heat, the original condition of things is restored.

The chief distinction between this and Lenoir's action can be ascertained by considering the nature of the expansion curve T_1 T_2. At the moment of ignition it may be taken that only a part of the gaseous mixture is burnt, the rest burning in successive portions. If this be so, then the expansion curve must show a marked difference from that of Lenoir's engine. An investigation of the curve shows this in the following most striking way. In the Appendix B are given data for determining the constant in the equation of the expansion curve T_1 T_2. It is found to be $m = 1 \cdot 37$, consequently the equation is $pv^{1 \cdot 37} =$ constant. From special investigation it is found that the constant k for the gases employed, that is to say, the ratio of specific heat under constant pressure to specific heat under constant volume, is $1 \cdot 37$.

Hence the Expansion Curve coincides with the Adiabatic.—Such a condition, as above explained, is only possible when the working fluid is continuously in contact with a body [which neither gives nor takes heat]. This is not actually the case, for the working fluid, whose temperature during expansion is very high, is in contact with the water-cooled cylinder, which necessarily, during the whole period of expansion, abstracts heat, so that, no source of heat being present, the curve must depart from the adiabatic, having a higher value for m, and consequently approaching more rapidly the axis of abscissæ. As this is not the fact, there is only one explanation possible :—

The compressed gaseous mixture is not all burnt at the explosion, indicated by the line m_0; but a considerable portion of it continues to burn during the expansion, and exactly that quantity of heat which is thus imparted to the fluid is abstracted by the water-casing as waste heat. The heat thus abstracted being in the Otto engine exactly equal to that imparted, the result is an adiabatic expansion curve which requires that the heat should remain constant.

A still more conclusive proof is afforded by another method :—In Appendix B are shown the quantities of heat that are imparted or abstracted at various points of the expansion.

The heat produced by the free combustion of the gas would amount altogether to 9870 calories; the actual production during the part of the stroke corresponding to T_0 T_1 amounts only to 5456 calories, so that there is a balance of 4414 calories, that can only be generated during the rest of the stroke.

Hence it follows that :—

At the explosion only 55 per cent. of the heat of combustion is developed, the remaining 45 per cent. being utilized by continued combustion after the explosion.

---

[1] [50 mm. = max. pressure.
4·7 ,, = 1 atmosphere.
If 1 atmosphere = 14·7 lbs. per sq. inch, maximum absolute pressure = 156 lbs. per sq. inch approximately.]

Appendix A to Dr. Slaby's Report.

Calometric Experiments with a 4-Horse Otto Gas-Engine, No. 5,460. Deutz, 3rd August, 1881.

1.—*Dimensions of the Engine.*

Diameter of cylinder	171·9 millimetres.
Stroke	340·0 ,,
Compression space	4,770 cub. centim.
Volume displaced by piston	7,888 cub. centim.
Total	12,658

The compression space is thus 0·6 of the volume displaced by the piston.

II.—*Power of the Engine.*

Duration of trial	½ hour.
Dynamometer lever	0·669 metres
Constant load	30·5 kilogr.
Total number of revolutions	4,702.
,, ,, explosions	2,351.
Average number of revolutions per minute. .	156·7.

Power $\frac{30\cdot 5 \times 0\cdot 669 \times 156\cdot 7}{716\cdot 2} = 4\cdot 46$ horses.[1]

III.—*Indicator Diagram.*[2]

No.	Time.	Area.
1	5 ,, 0′	1,800 square millimetre.
2	5 ,, 4	1,804 ,, ,,
3	5 ,, 6	1,800 ,, ,,
4	5 ,, 8	1,760 ,, ,,
5	5 ,, 11	1,792 ,, ,,
6	5 ,, 13	1,788 ,, ,,
7	5 ,, 14	1,816 ,, ,,
8	5 ,, 15	1,776 ,, ,,
9	5 ,, 17	1,752 ,, ,,
10	5 ,, 18	1,792 ,, ,,
11	5 ,, 20	1,776 ,, ,,
12	5 ,, 21	1,735 ,, ,,
13	5 ,, 22	1,730 ,, ,,
14	5 ,, 23	1,735 ,, ,,
15	5 ,, 24	1,718 ,, ,,
16	5 ,, 25	1,722 ,, ,,
17	5 ,, 26	1,775 ,, ,,
18	5 ,, 27	1,770 ,, ,,
19	5 ,, 29	1,760 ,, ,,
20	5 ,, 30	1,715 ,, ,,
	Total	35,316

[1] [4·4 English HP.]

Average area	1,766 square millimetres.
Constant length of diagrams	101 millimetres.
Mean ordinate	17·48 ,,
Scale of indicator . . .	4·7 millimetres = 1 atmosphere.
Average pressure . . .	3·72 kilograms per square centimetre.

$$\text{Indicated HP.}\ \frac{0\cdot1719^2 \times \pi \times 37{,}200 \times 0\cdot34 \times 166\cdot7}{4 \times 60 \times 75 \times 2} = 5\cdot11 \text{ horses.}[1]$$

$$\text{Efficiency} = \frac{\text{Brake power}}{\text{Indicated power}} = 0\cdot87.$$

IV.—*Gas Expenditure.*

Consumption exclusive of igniting flame . . .	2·020 cubic metres.
,, per [brake] HP. per hour . . .	0·906 ,,
,, for ignition per hour	0·078 ,,

V.—*Cooling Water Supply.*

Total quantity of water . . . . 107·25 litres.

Temperatures in cylinder casing indicated by inserted thermometer

5 ,, 0′	60·0° C.
5 ,, 1	60·0
5 ,, 2	60·5
5 ,, 3	61·0
5 ,, 4	61·0
5 ,, 5	61·5
5 ,, 6	61·5
5 ,, 7	62·0
5 ,, 8	62·5
5 ,, 9	62·5
5 ,, 10	62·5
5 ,, 11	63·0
5 ,, 12	63·5
5 ,, 13	64·5
5 ,, 14	64·0
5 ,, 15	64·5
5 ,, 16	65·0
5 ,, 17	64·5
5 ,, 18	64·0
5 ,, 19	63·5
5 ,, 20	63·0
5 ,, 21	62·5
5 ,, 22	62·0
5 ,, 23	61·5
5 ,, 24	61·5
5 ,, 25	60·5
5 ,, 26	60·0
5 ,, 27	60·0
5 ,, 28	58·5
5 ,, 29	58·0
Mean	62°
	15° Mean temperature of entering water.
	47° Elevation of temperature of the water.

[1] [5·04 English HP.]

VI.—*Temperature of Discharged Products of Combustion,*

Measured in the discharge-pipe, which was carefully protected against cooling. Zinc was melted, but antimony was not.

Melting-point of zinc (according to Mousson) . . .	423° C.
,, ,, antimony	432° C.

VII.—*Composition of Explosive Mixture.*

2,351 explosions consumed 2·020 cubic metres.

Each charge	0·000,859	cubic metres.
Mixture of air and gas for each charge .	0·007,888	,,
Charge ,, ,, ,, ,, .	0·007,029	,,
Residue ,, ,, ,, ,, .	0·004,770	,,
Total of air-charge and residue	0·011,799	,,

Relation of volumes $\frac{\text{gas}}{\text{air and residue}} = \frac{1}{13\cdot73}, \frac{\text{gas}}{\text{air}} = \frac{1}{8\cdot18}$

Weights . . . ,, $\frac{1}{29\cdot75}$,, $\frac{1}{19\cdot7}$

VIII.—*Computation of the Heating Power of Illuminating Gas.*

According to the analysis of the gas at the Gas-Motoren Fabrik, Deutz, as given by the town gasworks of Cologne, it consists of—

Simple carburetted hydrogen,	CH_4	0·344
Double ,, ,,	C_2H_4	0·035
Hydrogen	H	0·569
Carbonic oxide . . .	CO	0·052
		1·000

In the following Table are presented the proportions of the ingredients and their heating powers :—

	Cubic Metre.	Weight of 1 Cubic Metre.	Weight.	Heating effect of 1 Kilogram.	Heating effect of the proportion in 1 Cubic Metre of Gas.
CH_4 . . .	0·344	0·71	0·244	13,100 cal.[1]	3,196·40 cal.
C_2H_4 . . .	0·035	1·26	0·044	1,190 ,,	523·60 ,,
H . . .	0·569	0·09	0·051	29,350 ,,	1,496·85 ,,
CO . . .	0·052	1·26	0·065	2,390 ,,	155·35 ,,
	1·000		0·404		5,372·20 ,,

Thus 1 cubic metre of the Deutz gas must produce 5,372·2 calories. This estimate, however, is based on the assumption that the steam produced in the

[1] [The calorie used here is the quantity of heat required to raise one kilogram of water 1° Centigrade.]

combustion is condensed. Computation shows that 0·9 kilogram of steam i produced, which would take up $0 \cdot 9 \times 540 = 486$ calories. Deducting this, th actual heating power utilized is 4,886 calories.

As 1 cubic metre of the gas weighs 0·404 kilogram, the heating power o 1 kilogram amounts to

$$H = \frac{4,886}{0 \cdot 404} = 12,094 \text{ calories.}$$

Appendix B to Dr. Slaby's Report.

Calometric Investigation. (See Fig. 31.)

The length of the expansion diagram being 101 millimetres, and the compression volume being 0·6 of the volume passed over by the piston during expansion, the distance of the origin of the co-ordinates is $101 \times 0 \cdot 6 = 60 \cdot 6$ mm. to the left of the beginning of the diagram.

The diagram on which the investigation is based is that taken at 5 h. 29 min., having area 1,760 square millimetres. The dotted line is the figure taken, the full line figure being calculated. It is composed of four transitions, with three expansion curves and one compression curve, TT_0, T_0T_1 T_1T_2, and T_2T. The curves having an equation of the form $p\,v^m =$ constant, in which p is the pressure and v the volume, and m is a constant, either integral or fractional, positive or negative.

Computation of the constant m.

1. Compression curve TT_0

$$\frac{15}{5 \cdot 6} = \left(\frac{161 \cdot 6}{60 \cdot 6}\right)^m \qquad m = 1 \cdot 00.$$

2. Expansion curve T_0T_1,

$$\frac{15}{50} = \left(\frac{66 \cdot 5}{60 \cdot 6}\right)^{m_0} \qquad m_0 = -12 \cdot 95.$$

3. Expansion curve T_1T_2,

$$\frac{31 \cdot 2}{17 \cdot 5} = \left(\frac{138}{90 \cdot 7}\right)^{m_1} \qquad m_1 = 1 \cdot 37.$$

4. Expansion curve T_2T,

$$\frac{15 \cdot 5}{5 \cdot 6} = \left(\frac{161 \cdot 6}{152 \cdot 5}\right)^{m_2} \qquad m_2 = 17 \cdot 56.$$

Density of the Gaseous Mixture before Combustion.—The density of gas of which 1 cubic metre weighs 0·404 kilogram is

$$d = \frac{0 \cdot 404}{1 \cdot 293} = 0 \cdot 312.$$

The density of the gaseous mixture before combustion is according to Grashof (Resultate aus der mech. Wärme Theorie, p. 539)

$$\delta = \frac{8 \cdot 18 + 0 \cdot 312}{8 \cdot 18 + 1} = 0 \cdot 925.$$

Density of the Gaseous Mixture after Combustion.—When the gaseous mixture is completely burned, there is a moderate increase of density of the working

fluid. Indicating the density of the products of combustion by Δ, there is according to Grashof, when the mixture consists of 1 cubic metre of gas with 8 cubic metres of air, the ratio

$$\frac{\Delta}{\delta} = 1 \cdot 024.$$

Computation of the specific heat of the products of combustion according to Grashof (*a.a.o.*) :—

$$\left.\begin{aligned} C^1_p &= \frac{0 \cdot 2375 \times 8 \cdot 18 + 0 \cdot 343}{8 \cdot 18 + 0 \cdot 48} = 0 \cdot 264 \\ C^1_v &= \frac{0 \cdot 1684 \times 8 \cdot 18 + 0 \cdot 286}{8 \cdot 18 + 0 \cdot 48} = 0 \cdot 192 \end{aligned}\right\} \frac{C^1_p}{C^1_v} = k^1 = 1 \cdot 375.$$

Computation of the temperatures :—

$$\frac{T_0}{T} = \frac{p_0 v_0}{p v} = \frac{15 \times 60 \cdot 6}{5 \cdot 6 \times 161 \cdot 6} = 1 \cdot 00$$

$$\frac{T_1}{T} = 1 \cdot 024 \frac{p_1 v_1}{p v} = 1 \cdot 024 \frac{50 \times 66 \cdot 5}{5 \cdot 6 \times 161 \cdot 6} = 3 \cdot 76$$

$$\frac{T_2}{T} = 1 \cdot 024 \frac{p_2 v_2}{p v} = 1 \cdot 024 \frac{15 \cdot 5 \times 152 \cdot 5}{5 \cdot 6 \times 161 \cdot 6} = 2 \cdot 67.$$

Computation of the individual additions and abstractions of heat :—

The heat absorbed or added per kilogram of working fluid expanding according to any curve is expressed by the general formula $Q = C \int d\, T$, in which the constant C indicates the specific heat belonging to the particular expansion curve. Its value is found by the formula $C = \frac{m - k}{m - 1} C_v$, (Lenner, Thermodynamic theory, p. 144), in which m is the constant exponent, C_v the specific heat for constant volume, and k the ratio of the specific heat under constant pressure to that under constant volume.

$$C_0 = \frac{-12 \cdot 95 - 1 \cdot 37}{-12 \cdot 95 - 1} \times 0 \cdot 192 = 0 \cdot 197$$

$$C_1 = 0$$

$$C_2 = \frac{17 \cdot 56 - 1 \cdot 37}{17 \cdot 56 - 1} \times 0 \cdot 192 = 0 \cdot 187.$$

Marking now the accessions of heat for the curves m_0 m_1 and m_2 by the symbols Q_0 Q_1 Q_2

$$Q_0 = C_0 (T_1 - T_0) = 0 \cdot 197 (3 \cdot 76 - 1) T = 0 \cdot 5437 T$$

$$Q_1 = 0$$

$$Q_2 = C_2 (T - T_2) = 0 \cdot 187 (1 - 2 \cdot 67) T = - 0 \cdot 3123 T.$$

Hence it follows that during the curve m_0 a large accession of heat takes place; it indicates the explosion part of the diagram during which the greater portion of the gas in the mixture comes to, so to speak, spontaneous combustion.

During the expansion curve the heat accession Q_1 is 0, the curve being adiabatic, as was shown by the equality of m_1 with k.

The heat quantity Q_2 is negative, consequently during the change of con-

dition m_2 heat must be abstracted, this being found in the discharged products of combustion.

In order now to compute the accessions and abstractions of heat during the continued working of the engine, it is to be observed that the working fluid consists of 1 kilogram of gas and 29·75 kilograms of air and residuary products of combustion. During the trial 2·02 cubic metres of gas were used, that is $2 \cdot 02 \times 0 \cdot 404$ kilograms, making a total mixture of $(1+29 \cdot 75) \times 0 \cdot 404 \times 2 \cdot 02$ kilos. of working fluid. We therefore obtain the heat during the whole trial by multiplying the ascertained value of 1 kilo. of working fluid by this factor. Indicating the products respectively by O_0 and O_2 we have,

$$O_0 = 30 \cdot 75 \times 0 \cdot 404 \times 2 \cdot 02 \times 0 \cdot 5437 \text{ T} = 13 \cdot 641 \text{ T}.$$

$$O_2 = -30 \cdot 75 \times 0 \cdot 404 \times 2 \cdot 02 \times 0 \cdot 3123 \text{ T} = -7 \cdot 835 \text{ T}.$$

There is still to be considered the application of this heat by accession or abstraction during the performance of the curve m. The calculation gave $m = 1$, so that the curve has the equation $pv = p_0 v_0$, or is the isothermal curve according to Boyle's law, representing the compression of the fluid under constant temperature. As the compression developes heat, the above condition is only possible when the fluid under compression is in contact with a body that can abstract heat, which is the case with the water-jacket of the cylinder.

For reckoning the quantity of heat thus abstracted we cannot employ the above formula. We therefore take another method. The total value of the heat can also be determined by the work of compression, which can be ascertained from the diagram. The area is 768 square millimetres. As the area 1,766 square millimetres of the whole diagram is equivalent to 5·11 HP., this part is found from the proportion,

$$1766 : 5 \cdot 11 :: 768 : x = 2 \cdot 22 \text{ horse},$$

and $2 \cdot 22 \times 75 \times 60 \times 30 = 299{,}700$ kilogrammetres, or its equivalent

$$O = \frac{299{,}700}{424} = 706 \cdot 839 \text{ calories}.$$

Before we can draw further conclusions from the computed heat, we must make definite assumptions in reference to the lowest temperature T of the cycle.

It is disadvantageous to deduce this from the measured temperature of the expelled products of combustion, as the drawing in of fresh cool air, which mingles with the residuary products, makes a great alteration.

It is not necessary to determine the principal temperature by estimate; it can be obtained by calculation from the results obtained.

We have in the cycle only one accession of heat, namely, in the course of m_0, which is O_0. In the computation O_2 as well as O is to be taken as an abstraction of heat. The difference $O_0 - (O + O_2)$ expresses the heat translated into work, which is measured as the indicated work.

Hence for determining T we have the equation—

$$13 \cdot 641 \text{ T} - 7 \cdot 835 \text{ T} - 706 \cdot 839 = \frac{5 \cdot 11 \times 75 \times 60 \times 30}{424}.$$

T = 400; and, further, from the preceding,

$T_0 = 400$,

$T_1 = 1{,}504$,

$T_2 = 1{,}068$.

In order to get these temperatures according to the ordinary scale, it is only necessary to substract 273°.

We can now divide the heat as follows:—

1. Total from combustion of
$$2\cdot 02 \text{ cubic metres, free heat, } 2\cdot 02 \times 4{,}886 = 9{,}870 \text{ cal.}$$
2. Heat converted into the indicated work,
$$\frac{5\cdot 11 \times 75 \times 60 \times 30}{424} = 1{,}626 \text{ ,,}$$
3. Heat abstracted by the cooling water,
$$107\cdot 25 \times 47 = 5{,}041 \text{ ,,}$$
4. Heat carried away by the discharged products . . . . $O_2 = 7\cdot 835 \times 400 = 3{,}134$,,

The total of 2, 3, and 4 amounts to . . . . 9,801 ,,

so that the slight difference between this and 1, viz., 70 calories, may be neglected; probably it is due to conduction and radiation.

Reducing to unity, we have the following:—

Converted into work.	0·16
Abstracted by cooling water	0·51
,, by expelled products	0·31
,, by conduction and radiation	0·02
Total	1·00

What heat is liberated at the explosion?

$$O_0 = 13\cdot 641 \times 400 = 5{,}456 \text{ calories.}$$

which is 55 per cent. of the total heat produced by the combustion of the gas.

TABULAR VIEW of the CHIEF RESULTS.

—	Lenoir.	Otto.
	Tresca's Experiments.	Slaby's Experiments.
Gas consumed per HP. per hour .	2·69 cub. metres	0·90 cub. metres
Cooling water ,, ,, .	122 litres From 10° to 92°	48 litres From 15° to 62°
Utilization of the heat—		
1. Converted into work	4 per cent.[1]	16 per cent.[2]
2. Abstracted by cooling water .	66 ,,	51 ,,
3. ,, by expelled products and by conduction and radiation	30[3] ,,	33 ,,
m for expansion curve	2	1·37
Heat set free at explosion . . .	100 per cent.	55 per cent.
,, developed during expansion	0 ,,	45 ,,

[1] Tresca gives work as per dynamometer, not indicated work.
[2] Indicated work.
[3] Including loss.

APPENDIX V.

Physical Constants relating to Coal-gas and its combustion.

Translated from "Resultate aus der mechanischen Wärme Theorie," by Dr. F. Grashof, Heidelberg, 1870.

One cubic metre of coal-gas contains on the average—

0·42 cubic metre of	$C H_4$
0·08 " "	$C_2 H_4$
0·40 " "	hydrogen.
0·07 " "	carbonic oxide.
0·03 " "	nitrogen.

If, therefore, all volumes and specific weights (weights of 1 cubic metre) are referred to the normal atmospheric pressure (0·76 metre of mercury) and 15° Centigrade, and the densities referred to that of air as unity, then for the composition referred to above we have:—

Specific weight of the gas . . . . $W_0 = 0{\cdot}535$ kilogram.

" " of atmosphere . . . . . . $w_0 = 1{\cdot}225$ "

Density of the gas . . . . $\Delta_0 = \frac{W_0}{w_0} = 0{\cdot}4367$ "

Heating power of 1 kilogram of the gas. . . $C_1 = 10430$ calories.[1]

Heating power of 1 cubic metre of the gas, $C = W_0\, C_1 = 5580$ "

Weight of air required for complete combustion of 1 kilogram of gas . . . . $L_1 = 14{\cdot}5$ kilograms.

Volume of air for complete combustion of 1 cubic metre of gas . . . . $L = 6{\cdot}3$ cubic metres.

When 1 cubic metre of gas is mixed with b cubic metres of air, the specific weight of the mixture is—

$$w = \frac{1{\cdot}225\, b + 0{\cdot}535}{b + 1}.$$

The density δ is—

$$\frac{w}{1{\cdot}225} = \frac{b + 0{\cdot}4367}{b + 1}$$

After ignition and perfect combustion (assuming that b is greater than 6·3) the products of combustion (carbonic acid, water, nitrogen, and excess of air) will have the density—

$$\Delta = \frac{b + 0{\cdot}48}{b + 0{\cdot}83}.$$

The specific heat for constant pressure will be—

$$K_p = \frac{0{\cdot}2375\, b + 0{\cdot}343}{b + 0{\cdot}48}.$$

and the specific heat for constant volume—

$$K_v = \frac{0{\cdot}1684\, b + 0{\cdot}286}{b + 0{\cdot}48},$$

[1] The calorie is the heat required to raise one kilogram of water at its maximum density 1° Centigrade.

If, however, in the space where the mixture is ignited there should be liquid water, as in the Hugon gas-engine, say q litres or kilograms per cubic metre of gas at atmospheric pressure and 15° Centigrade; then for $b + 1$ cubic metres of gas mixture let Δ_1 be the density after ignition, let K'_p be the specific heat for constant pressure, and K'_v the specific heat for constant volume; we shall have—

$$\Delta_1 = \frac{(b+1)\,w + q}{\frac{(b+1)\,w}{\Delta} + 1 \cdot 6\, q}$$

$$K'_p = \frac{(b+1)\,w\,K_p + 0 \cdot 48\, q}{(b+1)\,w + q}$$

$$K'_v = K'_p - \frac{0 \cdot 069}{\Delta_1}.$$

The chemical re-arrangement of the atoms is accompanied by an increase in the density, according to the following ratios:—

$$\text{for } b = 8, \quad 10, \quad 12, \quad 14$$

$$\theta = \frac{\Delta}{\delta} = 1 \cdot 024,\ 1 \cdot 020,\ 1 \cdot 017,\ 1 \cdot 014.$$

Moreover, let τ_0 be the absolute temperature in degrees Centigrade, and p_0 the pressure in kilograms per square metre for the mixture before lighting, and τ_1 and p_1 the corresponding temperature and pressure immediately after the ignition; then assuming that per cubic metre of gas α C calories are instantly developed at constant volume, we have approximately

$$\tau_1 - \tau_0 = \frac{1}{K_v} \frac{\alpha\, C}{(b+1)\,w}; \quad \frac{p}{p_0} = \frac{\tau_1}{\theta\, \tau_0}.$$

The formulæ are most correct when α is near to unity. When water is present,

$$\tau_1 - \tau_0 = \frac{1}{K'_v} \frac{\alpha\,(C - 600\, q)}{(b+1)\,w + q}$$

$$\frac{p_1}{p_0} = \left(\frac{1}{\theta} + \frac{1 \cdot 306\, q}{b+1}\right) \frac{\tau_1}{\tau_0}.$$

The pressure is diminished less than the absolute temperature by the presence of water.

From experiments on gas machines, α may be taken at from $\frac{2}{3}$ to $\frac{3}{4}$.

[Adhering to the Centigrade scale, the above expressions can all be used for English measures, as will be seen from the following considerations.

The density is referred to that of air. The specific heats are referred to that of water. The change of pressures is given as a ratio, and the quantity of water is also expressed as a fraction of the weight of the gas, whatever may be the unit employed. The heating power of a lb. of gas is easily calculated from that of a kilogram. It may be noted in passing that the value of the atmospheric pressure used by Grashof, though corresponding to that of 760 millimetres of mercury, is not the English value 2,116·4 lbs. per square foot, but appears to be equivalent to 2,107 English lbs. per square foot.

The composition of Grashof's gas may be compared with that of London and Manchester coal-gas cited by Clerk.

1 lb. of Manchester gas gave a heating value of 4,940 calories, or 15,147,000 foot-lbs.

1 lb. of London gas, 5,664 calories, or 17,370,000 foot-lbs.

1 lb. of Grashof's gas, 4,731 calories, or 14,510,000 foot-lbs.

It did not appear to me worth while to use the above computations in comparing the various efficiencies of engines of different types, in Appendix II. The relative merits would have been little altered, and the labour of the calculations much increased.]

APPENDIX VI.

Dowson's Gas.—Mr. J. Emerson Dowson in 1883 submitted a Paper[1] on his valuable improvements in the manufacture of cheap gas for motor engines, to which little more need as yet be added. Each lb. of anthracite produces from 75 to 76 cubic feet of gas at atmospheric pressure and a temperature of 10° C.

In the Otto engines the volume of Dowson gas required is five times that of ordinary gas to give the same power; 110 cubic feet per HP. per hour being burnt in an engine indicating about 4 HP., and about 90 cubic feet per HP. per hour in an engine indicating about 30 HP. One cubic foot of Dowson gas requires, however, only 1·1 cubic foot of air for its complete combustion, whereas in an Otto engine as much as 12 volumes of air are mixed with each volume of ordinary coal-gas. Hence Mr. Dowson arrives at the result that without altering the dimensions of the cylinder it is possible to pass into it the five volumes required of his gas, with the 5·5 volumes of air theoretically required for its combustion, and to have in addition an ample excess of air present. In converting anthracite coal into Dowson gas, we lose only from 15 to 20 per cent. of the total heating power. The average fuel consumption at Messrs. Crossley's works, where Dowson gas is used for several engines, is 1·3 lb. per I.HP. per hour, and with one engine indicating about 32 HP., and tested separately, it was as low as 1·1 lb. per HP. per hour, corresponding to 83·6 cubic feet of the gas. This is a most remarkable achievement. The heat developed by the combustion of 1 cubic foot of Dowson gas at 0° Centigrade and atmospheric pressure is 125,000 foot-lbs., or about one quarter of that developed by Manchester coal-gas per cubic foot. The heat developed by 1 lb. of Dowson gas is about 9,000,000 foot-lbs.; at 0° Centigrade it weighs about 0·014 lbs. per cubic foot. It is sometimes supposed that the Dowson apparatus takes up too much room, but an engine indicating from 40 to 50 HP. can now be worked with plant occupying a ground space of 10 feet by 8 feet, or less than is required for the horizontal boiler of a steam-engine of the same power. For the cost of production the reader is referred to Mr. Dowson's Paper.

APPENDIX VII.

As Robert and James Stirling's patents for air-engines are of great interest in the history of heat-engines, and as the first patent is out of print, I have thought it desirable to include a complete report of that specification, with its illustrations (see Plate 4, Figs. I. to VI.). The spherical plates E E are the first example of the regenerator. This invention reappears, in a greatly improved form, in the second patent.

[1] Minutes of Proceedings Inst. C.E., vol. lxxiii., p. 311.

A.D. 1827.—No. 5456. AIR ENGINES.

R. and J. Stirling's Specification.

To all to whom these Presents shall come, Robert Stirling, clerk, minister of Galston, in the county of Ayr, North Britain, and James Stirling, engineer in Glasgow, in the county of Lanark, North Britain, send greeting. Whereas . . .

Now know ye, that the said Robert Stirling and James Stirling do, by this instrument in writing, under their hands and seals duly executed, describe and ascertain the nature of their invention, and the method in which the same is to be performed (that is to say):—

A, A, B, B, Figure First, is a vertical section (passing through the axis) of the under part of the air-vessel, which part consists of one piece of cast-iron, having the bottom B, B, B, of a spherical form, and the sides A, B, A, B, cylindrical; the flanch A, A, serves for bolting this vessel to its cover or lid, and the flanch C, C, for supporting it upon the building of the furnace. The part of the side which lies between the two flanches A and C is turned correctly on the inside, into a form which approaches so nearly to a true cylinder that its diameter at A, the mouth of the vessel, is about one-thousandth part greater than its diameter at the flanch C. Into this vessel is introduced and accurately fitted the plunger D, D, E, E, which consists of the following parts: F, G, H, is a vertical section of a horizontal ring of cast iron, which is supported by four arms, similar to G, I, placed at equal distances round its circumference, and united at the centre to a rod of malleable iron F, K, truly turned and polished, and called the plunger-rod. Each of the arms G, I, has a part H, L, projecting perpendicularly from its junction with the ring F, G, H, and having its opposite sides formed into planes parallel to the plunger-rod, and to that diameter of the circular ring above-mentioned, which passes through said projecting parts respectively. The parallel sides of these projecting parts or guides are polished, and work upon pieces of brass M, fixed in the cover of the air vessel to keep the plunger steady in its perpendicular motion. Figure Sixth is a bird's-eye view, upon a reduced scale, of the framework of the plunger. R, R, R, R, is the cast-iron ring; A, A, A, A, the arms by which it is supported; G, G, G, G, the guides; *b*, *b*, the brasses upon which the guides work, and P the plunger-rod. The ring F, G, H, Figure First, the arms G, I, and the guides H, L, are all cast in one piece, and serve for supporting and moving the following parts of the plunger, which are of sheet iron. D, F, is a conical ring of sheet iron, of the thickness of $\frac{1}{15}$ inch, riveted at F to the cast-iron ring above mentioned, and also riveted at D to a cylindrical ring of sheet iron D, E, of the thickness of $\frac{1}{12}$ inch; D, E, is again riveted, as represented at E, to the spherical part E, E, E, which is also composed of plates of sheet iron of the thickness of $\frac{1}{8}$ inch, riveted together and hammered so as to apply exactly to the upper surface of the spherical bottom B, B, B. A similar compound spherical part of sheet iron, $\frac{1}{16}$ inch in thickness, F, F, F, is riveted to the cast-iron ring F, G, H, and so adjusted as to be everywhere about $3\frac{1}{2}$ or 4 inches distant from the spherical plate E, E, E; both of these spherical plates are pierced with a multitude of holes about $\frac{1}{4}$-inch in diameter, and not more than 1 inch distant from one another. Before the sheet-iron box now described is finally riveted together at D, the space E, F, E, is filled up with successive layers of plates of the thinnest sheet iron in use, pierced with holes, as already described, stamped or hammered into a spherical form, and kept at the distance of two or three times their own thickness from one another by small indentations formed in the unperforated parts by a proper punch or die. Figure Second, which is a vertical section of a small portion of these plates, represents the nature of the

said indentations, and also the holes already described; *a a* are the indentations, and *b*, *b*, *b*, the holes. The holes which are made in these thin plates are arranged in rows at equal distances from one another, and each successive layer is so placed that its holes shall not be opposite to those of the layer beneath it. The object of this arrangement is to spread the air more completely over the plates in passing upwards and downwards, and to heat and cool it more effectually. The space between the conical part D, F, Figure First, and the cylindrical part, D, E, is in like manner filled up with plates of the thinnest sheet iron, without holes, and kept at a small distance from one another by indentations as already described. Instead of filling the space or cavity E, F, E, with plates of iron or other metal, we sometimes fill it with small pieces of stone or burnt clay, glass, stoneware, or any similar bodies, as small as possible, provided they do not pass through the holes of the sheet-iron box. At present, however, we prefer filling the cavity with plates, as above mentioned. The outer plate of the plunger D, E, is kept on all sides distant from the interior surface of the air-vessel about the three-hundredth part of its diameter, and in order as much as possible to prevent the air from passing between them; a thin plate D, N, which is partly slit into narrow threads, as represented at Figure Third, is riveted or screwed to the plunger at D, Figure First, extending round its whole circumference, and its narrow stripes are bent outwards, so as to touch slightly the turned part of the air vessel round its whole circumference. The cover of the air vessel O, P, P, O, is of cast-iron, and of such a form that when its flanch O is applied to the flanch A, and the plunger drawn upwards till the point D touch the flanch O, the remaining part of the cover shall apply as closely as possible to the upper surface of the plunger. This cover is bolted to the lower part of the air-vessel by the bolts Q, Q, and the joining is rendered air-tight by a stripe of sheet lead interposed between the flanches A and O. In the centre of this cover is a perpendicular tube R, R, for receiving the plunger-rod F, K, and upon the top of this tube a stuffing-box, packed with hemp and oiled, to prevent the passage of air, and at the same time to permit the plunger to be moved. Near the circumference of the cover there are four projecting cavities S, S, which receive the guides of the plunger, and the brasses upon which they slide or work. These cavities are provided with air-tight covers, which, upon being removed, permit the brasses to be drawn upwards, for the purpose of being adjusted so as to keep the plunger in its proper position, and in the centre of these covers there are stop-cocks T and U, so constructed as to admit oil at any time for lubricating the guides, and not to permit the escape of air. The movable part of these stop-cocks is turned in the manner represented at U; the oil is then poured in from above, and by turning it into the position represented at T, the oil is permitted to descend. In like manner oil is introduced to lubricate the piston and other parts which require it. Lastly, there is an aperture made in the cover of the air-vessel, represented by the dotted lines at V, by which the air in the air-vessel is permitted to communicate with that in the cylinder, and at all other points the said air-vessel is made air-tight. The whole of Figure First is drawn to a scale of 2 inches to a foot,[1] except where the dimensions have been expressly specified in words. Figure Fourth is an elevation, and Figure Fifth a bird's-eye view, of the manner in which we apply the part of our invention above described, and combine it with others for producing a greater power in air-engines than has been hitherto attained. These figures are drawn to a scale of $\frac{3}{4}$ inch to a foot[1]; the same parts are in both figures, when visible, marked with the same letters, and the following description refers to both:—A, A, and B, B, are two air-vessels,

[1] Reduced one-half in Plate 4.

such as we have specified above, in which, however, the guides of the plungers are omitted in Fig. 4, to prevent confusion. The air-vessel A, A, is connected with the lower part of the cylinder C, C, by the pipe or nozzle D, and the air-vessel B, B, is connected by the pipe E, E, with the upper part of the cylinder, which has an air-tight cover, as in the best steam engines. By means of the plunger-rods, the cross-heads, and the side-rods, as represented in the figures, the plungers are connected to the opposite ends of the balance-beam F, G, which moves upon the fixed centre H. The interior diameter of the pipes or nozzles is one-fifth of the diameter of the cylinder, and one-fifteenth of that of the air vessels, and the stroke of each plunger is one-fourth of the stroke of the piston. The cylinder C, C, the air-pump I, I, one end of the crank-shaft K, K, and the pillar which supports the working beam, are supported upon the frame L, L, the greater part of which is formed into an air-tight vessel or magazine for containing a supply of condensed air or gas. For the purpose of procuring and maintaining this supply, the air-pump I, I, whose diameter and stroke are each half of those of the cylinder, and which has a solid piston and air-tight cover, is made to communicate to the magazine, both from above and below the piston, by proper pipes with self-acting valves, so constructed as to throw air continually into the magazine while the engine is at work. From the magazine (which has a safety-valve for the escape of the surplus air) a communication is made with the nozzles D and E by means of the small pipes M and N, and these latter pipes are provided with self-acting valves, which permit the air to pass from the magazine into the nozzles and cylinder, but prevent it from returning into the magazine. The piston-rods of the cylinder and air-pump are connected with the crank K, K, by a parallel joint, working beam, and connecting-rod, or by any of the means commonly employed in steam-engines. The crank-shaft K, K, carries a flywheel O, P, Q, and an eccentric wheel or secondary crank, which last ought to be so adjusted that the stroke of the plungers is exactly half completed when the piston is on the point of having its motion reversed. The eccentric wheel communicates motion to the balance-beam and plungers in the following manner:—The eccentric rod R, R, communicates a reciprocating motion to the levers S, T, and S, U, which move upon the fixed centre or shaft S. The movable end of the lever S, U, is connected by the rod U, V, to the rod V, W, which in like manner moves upon the fixed point W, and the point V being thus made to rise and fall alternately, communicates a reciprocating vertical motion to the balance-beam and plungers through the rod V X. The operation of the whole engine is after this manner. We make a fire beneath each of the air-vessels A, A, and B, B, at such a distance that its heat may be equally diffused over the spherical bottoms, and at the same time we keep the upper part or cover of the said air-vessels as cold as possible, either by their own power of dispersing heat into the atmosphere, or by directing upon them a stream of air or water. When it is seen through a small aperture in the furnace that the smoke of the furnace is burnt off from the bottom of the air-vessels by the heat of the fire, the apparatus is ready for working, and we keep the bottoms as near as possible to this temperature while the engine is at work. Suppose now, therefore, the crank to be in the position represented in Figures Fourth and Fifth, and that by the revolution of the crank-shaft and eccentric wheel, or by moving the handle Y, the plunger in the air-vessel B, B, has been brought to the top, and the plunger in A, A, to the bottom. The air which was formerly above the plunger in the air-vessel B, B, has now been made to descend through the holes, in the thin plates of which the plunger is composed, and has been heated in its passage, and consequently its elasticity has been increased, as also its pressure upon the interior of the air-vessel, and upon the upper side of the piston in the

cylinder with which it communicates; in like manner the air which was formerly beneath the plunger in the air-vessel A, A, by passing upwards through the plates of the said plunger, has been cooled, and its elasticity and its pressure upon the lower side of the piston is diminished. The pressure upon the upper side of the piston therefore, being greater than that upon the lower side, the piston is forced downwards, the crank is drawn upwards, and an impulse is communicated to the flywheel, which moves round in the order of the letters O, P, Q, carrying along with it the eccentric wheel, which, drawing the eccentric rod towards the crank-shaft, depresses the point V, and thus reverses the position of the plungers and the pressure upon the piston, which, again, is forced upwards and gives another impulse to the fly, and so on continually. The engine is at first started or set in motion by detaching the eccentric rod from the lever S, T, and moving the plungers with the hand, like the valves in a steam-engine; and when the fly has acquired a sufficient momentum, the connection is restored. Also, in order to start at first with greater power, we sometimes employ the condensing power of the plungers as a substitute for the air-pump, to throw a supply of air into the magazine, and though we generally work the engine with common atmospheric air, yet, whenever a supply can be conveniently obtained of nitrogen, carbonic acid, or any permanent gas which does not readily corrode iron nor cause explosion, we use it with equal and in some respects greater advantage.

Know ye, also, that we the said Robert Stirling and James Stirling do not profess to be the first and sole inventors of all the parts which compose the engines now described, such as cylinders, pistons, valves, parallel joints, cranks, fly-wheels, and such other things which have been long in common use, nor of the principle of giving motion by means of the alternate expansion and contraction of air. But we have applied for and obtained His Majesty's Letters Patent as the true inventors of such applications or combinations of those elementary parts described above as enable us to produce a new manufacture of improved air engines.

In particular, our first improvement upon air-engines consists in giving to the air-vessel and plunger the form and structure represented in Figures First, Second, Third, and Sixth, and the description referring to them, by which we are enabled to make the thin plates or other bodies filling the plunger, which are necessary to retard the passage of heat upwards, serve also for heating and cooling the air.

Our second improvement upon air-engines consists in the application of two or more such air-vessels and plungers to one cylinder, so as to act alternately and equally upon opposite sides of the same piston.

Our third improvement upon air-engines consists in admitting air by means of valves into the cylinder or air-vessels, so as to keep up a greater pressure upon the piston when we do not wish to employ an air-pump.

And our fourth improvement consists in forcing through the said valves, by means of an air-pump, a greater quantity of air than could be introduced by the simple pressure of the atmosphere. It is for the invention of these four improvements only that we have applied for and obtained His Majesty's Letters Patent.

In witness whereof, &c.

J. and R. Stirlings' second patent, dated thirteen years later (No. 8652, 1840), shows that they had made considerable improvements in the practical details of the engine. Fig. 15A, Plate 2 shows the displacer, regenerator, and refrigerator, with the packing of the piston-rod, all well arranged, and such as might be adopted

to-day by any maker. They describe the vessel A, A, A, A, as made of cast iron, and proved to a pressure of 700 lbs. per square inch. The displacer consists of a cap of cast iron, *a*, *a*, *b*, *b*, having its bottom perforated with a number of holes, whose collective areas should be about one-twelfth of the area of the piston, and which are intended for the passage of the air. C, C, D, D, are alternate sheets of plane and fluted glass, the width of the passages not exceeding $\frac{1}{60}$ inch. The cover E E is perforated with a multitude of small holes for the passage of the air; the outer portion of the displacer (or driver, as they call it) F F is packed close with plates of plane glass or iron, to obstruct the passage of the heat from the air-vessel into the driver, and into the space E, B, B, E. The cooling apparatus, H, I, H, I, is a refrigerator, through which water circulates, and is constructed in a manner which enables it to bear a very high pressure. In the regenerator, which in this example forms part of the displacer and moves with it, rods of glass are described as being sometimes used instead of fluted plates. In another example the regenerator and refrigerator are shown separate from the displacer, and the regenerator is described as constructed with wide plates of sheet iron, the greater part of which are about $\frac{1}{40}$ inch in thickness, and kept at a distance of $\frac{1}{50}$ inch from one another by small ridges or dimples. The cooling apparatus in this example consists of copper pipes $\frac{1}{8}$ inch diameter within and $\frac{1}{4}$ inch without, and $\frac{1}{25}$ inch apart. They make the capacity of the cylinder, exclusive of the space occupied by the piston, about seven-tenths of the space left at the top of the air-vessel, when the driver is resting on the bottom. They use an air-pump to supply the waste of air by leakage, and likewise to fill a magazine of condensed air for starting the engine with full power. They commonly employ a pressure of 150 lbs. per square inch in the air-vessels when not heated. They test the refrigerator with a pressure of 400 lbs. per square inch.

The patent is full of details, and bears every mark of having been prepared as a description of well-proved designs.

20 March, 1884.

Sir J. W. BAZALGETTE, C.B., President,
in the Chair.

"On Compressed-Air and other Refrigerating-Machinery."

By A. C. Kirk, M. Inst. C.E.

The subject of this lecture is one of comparatively modern development. Thirty years ago the speculation of a small number of advanced scientific men, it is now a most important contribution to our well-being, and withal, I venture to prophesy, even yet only in its infancy.

When I add that to the use of refrigerating machines we are indebted for very much of the ice used in the tropics, for the production of our finest candles, for the better production of much of the beer we drink, better curing of the pork and bacon we eat, and that we depend on their use for vast supplies of the butcher meat we draw from our colonies and foreign countries, it will be seen how important the subject of mechanical refrigeration already is.

There are many other applications of such machines which it would occupy too much time to enumerate.

When we consider that both the construction and application of refrigerating machinery is but in its infancy, there can be no doubt that a wide and inviting field for its more extensive application and further improvement is ever opening before us.

The artificial production of ice has long been a matter of scientific curiosity in Europe, and of very practical importance in tropical countries.

Our older scientific treatises devoted much space to the composition of freezing mixtures, and to descriptions of methods adopted in India for producing thin ice on favourable nights by exposing water to the combined action of radiation and evaporation and suchlike. Such processes, however, did not to any practical extent meet the demand for ice, and besides, they do not come within the scope of this lecture.

Until the development of the mechanical theory of heat by Carnot, Joule, Thomson, Clausius, Rankine and others, no real

progress was made in mechanical refrigeration. Thus, when we turn to Trevithick's proposal (clever and original man though he was), in 1828, to compress air, cool it, and allow it to escape amongst the water to be cooled, the mechanical theory of heat tells us it would have been a total failure, for the simple reason, then unthought of, that the escaping air did no work as it expanded, and therefore would not have taken heat from the water.

In 1845 Dr. Gorrie of New Orleans made a great step by causing the compressed and cooled air to expand by working a piston in a cylinder against a resistance, the work done by the expanding air assisting to work the apparatus by which the air was compressed. This machine consisted of a cylinder, with a piston and suitable valves, by which air was compressed. During compression heat was evolved, due, as we know now, to the work spent in compression being transformed into heat.

This heat was removed by injecting water of the natural temperature into the cylinder during compression, so that really the air was maintained during compression at its natural temperature. As the air was compressed it escaped into a receiver, where any water in suspension was allowed to settle. The compressed air was then used to work a piston in a cylinder, like the piston and cylinder of a steam-engine, and thus in expanding to give out power which went to reduce the power spent in compression.

During expansion brine was injected into the cylinder, which, giving up its heat to the expanding air, was cooled.

The cold brine was used as a vehicle for abstracting heat from the water which was being frozen. Although the machine produced ice, neither it nor a larger one, built in London on the same plan, was a practical and commercial success.

The great step made by Dr. Gorrie was the introduction of a cylinder and piston, in which the expansion of the compressed air was carried out and thus made to do work.

From Dr. Siemens' report on a similar machine erected in London, we must infer that this was done rather with a view to recover part of the power spent in working the machine than from a clear appreciation that it was an essential condition to the production of cold that the air should do work.

Still, to Dr. Gorrie we must give the credit of being the first to produce cold by the mechanical compression and expansion of air.

It was not till the mechanical theory of heat was developed that any clear idea was formed of the processes essential to refrigeration.

Steam-engines and air-engines had advanced to almost their present state of perfection before this theory was worked out, and its application to the explanation and calculations of their performance was a test and illustration of its correctness. On the other hand, refrigerating machines owed their development on correct principles to the establishment of the mechanical theory of heat.

It must seem strange that the earliest successful attempts at constructing mechanical refrigerating machines should have been made with air as the medium through which power was applied to the abstraction of heat (a medium which had presented great difficulties when used for the production of power from heat), to the neglect of condensable vapours. These presented fewer difficulties of application, and the steam-engine, the oldest thoroughly successful and finished example of a heat motive-power engine, belonged to this type.

In 1856 Harrison patented a machine for producing cold by evaporation and recondensation, of the same type as the steam-engine, but using sulphuric ether as the medium, which in the hands of Messrs. Siebe became in a few years an efficient machine.

Carré's ammonia machine, in which the condensable vapour of ammonia, by its evaporation and recondensation as the medium, was proposed in 1859, in the hands of Messrs. Mignon and Rouart soon became also an efficient machine, by which energy in the direct form of heat was made a means of producing cold, without the intervention of a motive-power engine. These three processes, which were the earliest attempts at mechanical refrigeration, may be taken as types of all in use up to the present day.

Before, however, we proceed to describe actual refrigerating machines, or the means of applying to various purposes the cold produced, we must glance briefly at the theory of thermo-dynamics, in so far at least as it bears on the subject of the present lecture.

The proposition I wish to illustrate is very simple, and is this, that every refrigerating machine is only a thermo-dynamic engine in which the power is negative. In other words, instead of giving out power, power must be supplied from an exterior source to work it. When an engine receives heat at a higher temperature and rejects a portion of it at a lower temperature, the difference is the power given out—the power to do work. When the same engine absorbs heat at a low temperature and gives it out at a higher temperature, power must be applied to move it. A previous lecture you have heard will I hope enable me to make this intelligible in but few words.

When we use heat as a source of power, we take advantage of its property of causing the substance or medium we use to expand when heated and contract when cooled, and practically the substances employed are elastic incondensable gases or condensable vapours. And you know that power may be changed into heat at the rate of 772 foot-pounds as an equivalent to the quantity of heat which would raise one pound of water one degree Fahrenheit, in temperature. The converse problem can never be fully realized, that is, given a certain quantity of heat, we can never convert the whole of that into its equivalent in work, and the value of the heat to do work depends on the temperatures of the heat at our disposal.

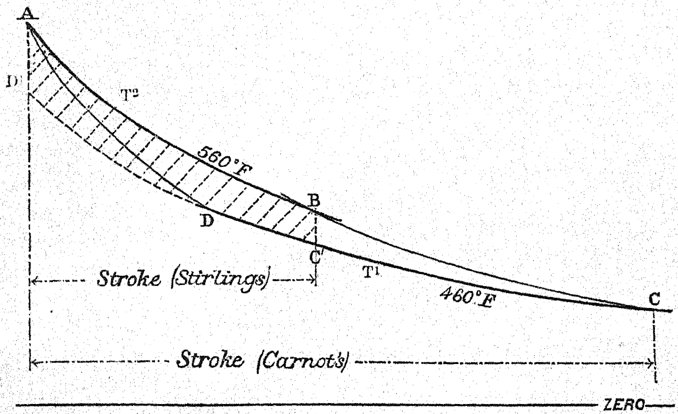
Take, as the simplest in theory, though not in practice, the case of the thermo-dynamic engine in which the medium is an elastic incondensable fluid, we shall say air. If a pound of air be allowed to expand in a cylinder pushing a piston against an equal resistance, and if we have a source of heat keeping the air at the same temperature while it is expanding, its pressure will fall much more slowly than if the air were not supplied with heat from any external source. The power thus given out while our pound of air expands some given number of times is in proportion to the absolute temperature of the air during expansion. If, on the other hand, no heat be supplied to the air during expansion, the pressure will fall more quickly. In both cases heat is converted into work in pushing the piston.

In the first case, while the air was maintained at a constant temperature from an outside source of heat, the heat continuously supplied is converted into work; while in the second, the heat converted into work is derived from the heat contained in the air when it commenced to expand and push the piston along. Thus under these latter conditions the expanding air will be cooled, the reverse taking place when we compress it.

Carnot's elementary engine is founded on these two conditions under which expansion can be conducted. While we expand air in a cylinder and supply heat to maintain the temperature constant, we have seen that we do work at the expense of heat. On the other hand, if we force the piston back, we shall spend the same work in compression as we got during expansion, and will have continually to remove as much heat from the air during compression as we formerly supplied during expansion. In this neither heat nor power will be consumed or produced. But if we could bring the air to a lower temperature before we compress it, we will then require to spend less power to compress it, and abstract

less heat from it, to prevent its temperature from rising. How the temperature of the air is to be lowered to that of compression and again raised to that of expansion we shall see later on. The excess of power got in expansion over power spent in compression is available to do work, while the heat due to the power spent in compression must be abstracted by some outward body, practically air or water, which fixes the lowest temperature at which the heat of compression can be abstracted. The above constitutes the essential idea of a thermo-dynamic engine in which air is the medium used, which we may describe graphically, thus—

FIG. 1.



Carnot's Cycle in full lines. Stirling's Cycle dotted.

Suppose our cylinder, containing a pound of air, has a hot cover on it, keeping the contained air at the constant absolute temperature T^2, while the piston moves from A to B, the air as it expands pushing the piston, will do work exactly in proportion to the quantity of heat supplied by the cover. Now, if we can only get the air reduced to the absolute temperature T^1, put a cover on the cylinder which will carry off any heat above T^1, and compress the air at this lower temperature T^1 from C to D as many times as we expanded it from A to B, we shall have done less work in compression than we got during expansion, in proportion to the temperatures, the difference being available to do external work. The question then is, how are we to cool the air in the cylinder from T^2 to T^1 and warm it again from T^1 to T^2 without loss of heat or energy?

In whatever way we carry it out, it resolves itself into storing up the heat as we cool the air, and restoring that heat to warm the air. There are two ways of doing this. The first is by converting

the heat into work as we cool the air from T^2 to T^1 in which state the heat can be stored, by a fly-wheel for instance, and again converting this work into heat to warm the air from T^1 to T^2. When the piston was moved to B suppose the source of heat removed, and the air allowed to push the piston further without receiving heat, but doing work all the time, and therefore cooling itself. By allowing the piston to move far enough we may reduce the air from the temperature T^2 to T^1, ready to undergo compression at the constant temperature T^1 as the piston moves from C to D—the heat generated during this compression being removed continuously. If now on the arrival of the piston at D we cease to remove the heat generated during compression, as the piston moves on from D to A the enclosed air will be raised in temperature to T^2 ready to repeat the operation. The cooling during the expansion from B to C becomes in fact heat stored up as energy to be again converted into heat during compression from D to A. This complete cycle of operations is called after Carnot, its discoverer.

There is yet another way, invented by R. Stirling, of effecting the same thing; but in this case as the temperature falls from T^2 to T^1 the heat in passing from B to C^1 is stored up directly as heat and is restored directly as heat from D^1 to A. Stirling called the apparatus for doing this a regenerator, and it consists of a mass of finely divided material, layers of wire gauze, for instance, through which the air is made to pass at B C^1 in its transmission from the temperature T^2 to T^1 and through which it is made to repass in the opposite direction, after compression at the temperature T^1 from D^1 to A. As the hot air passes from B to C^1, and from T^2 to T^1, each layer of the gauze, or other material, acquires very nearly the temperature of the air, all the layers of gauze being slightly warmed, while after compression, as the air returns from D^1 to A, it again absorbs from the material of the regenerator the heat left in it during the previous operation. Thus theoretically air may be passed through Stirling's regenerator from a hot chamber to a cold one, and *vice versâ*, without carrying with it heat from the hot chamber to the cold.

The diagram of a regenerator engine will be A B C^1 D^1 (Fig. 1), the area of which represents the power, and is exactly equal to A B C D. By the use of the regenerator the length of the cylinder is much reduced, from A C to A C^1.

In all heat-engines the temperature of rejection of heat is, as we pointed out above, limited by that of the surrounding air and water; and similarly if we convert a heat-engine into a refrige-

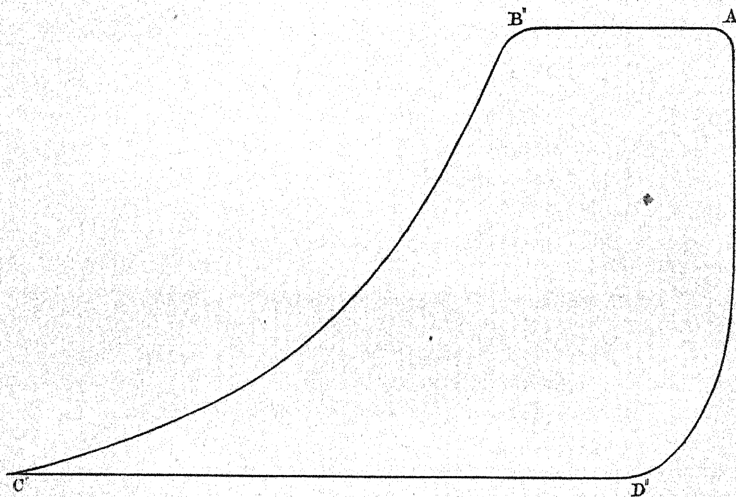
rator, we still cannot reject heat at a lower temperature than nature provides. One feature of the cycles of operations we have described is that we may reverse them. In other words, we may in Carnot's system raise the temperature of the air from T^1 to T^2 by compressing it adiabatically from C to B, that is, without allowing it to part with any of its heat during the process; from B to A compress it isothermally, that is, remove the heat as it is generated, and so maintain the air during the operation at the temperature T^2, we may then expand it adiabatically from A to D, and isothermally from D to C, during which operation it must absorb heat to maintain the temperature steadily at T^1. Here, however, while the power spent in the compression CB is neutralized by the power given out during the expansion AD, the heat rejected during compression from B to A, which represents power consumed, is greater than the heat absorbed during expansion from D to C, which represents the power generated. Thus power in proportion to the difference of temperature must be supplied to keep the machine moving.

It is obvious that we may, in the same way, reverse the cycle of operations where a regenerator is used, absorbing heat at a lower temperature during isothermal expansion, and rejecting it at a higher temperature during isothermal compression, work being consumed in proportion to the difference of temperature.

Having thus explained how it comes that a motive-power heat-engine, operating with air as a medium, passes into a refrigerating machine, it will take only a few words to show that the same holds good of motive-power engines, like the steam-engine, where the medium employed is a condensable vapour. In the case of the steam-engine the temperature at which heat is absorbed, T^2, is the temperature at which water boils under the pressure A'', while the temperature T^1 of rejection of heat, which cannot be lower than the natural temperature of water, is the temperature at which water boils at the corresponding pressure D''. The line A'' B'' (Fig. 2) is an isothermal, that is, the water in the form of steam expands from A'' to B'', absorbing heat in the boiler, this heat changing water into steam continuously as the piston moves from A'' to B''. Unlike the case of an incondensable gas which we have just considered, the pressure remains constant during isothermal expansion from A'' to B'', owing to the physical change the liquid undergoes. When the piston has reached B'' the steam moves it further, expanding now adiabatically, that is without further absorption of heat, till, for the sake of simplicity, we shall say the temperature T^1

is reached, and the piston has moved to C″. Saturated steam, such as we are dealing with, cannot be cooled as air can. If we abstract any heat from it, the effect is not only to cool it but to condense a certain quantity of it into water. Hence during expansion from B″ to C″, whatever heat is converted into work will be represented by the steam being cooled, and a part of it condensed. By availing ourselves of this same property, the mechanical compression from C″ to D″, which we had to resort to in the case of air, is dispensed with, for we can by abstracting heat at the temperature T^1 reduce the steam to water. This process of rejecting heat from C″ to D″ is carried on at a constant pressure in the same way as the absorption of heat was carried on from A″ to B″.

FIG. 2.



The resulting volume of water is so small, that the power spent in forcing it back into the boiler to be again converted into steam gas may be neglected. Thus the cycle of operations is completed, and practically simplified, by availing ourselves of the physical property water possesses of being converted by heat from a liquid to a gas, and by the abstraction of heat, again condensed into a liquid; but on the other hand the temperature of heat-absorption is limited by the temperature of evaporation under the available pressure.

Suppose now that T^2 were the natural temperature of water available for condensation, by reversing the series of operations we would compress the steam from C″ to B″ adiabatically, without it receiving or parting with heat; from B″ to A″ we should condense

it; we should then return the water to the boiler (which, as it would be passing from a higher pressure to a lower, it would do of itself) to D″. We should supply it with heat which it would absorb, boiling at the pressure D″ C″ and temperature T^1. We should again expend work in compressing it, and so on.

Thus we have a complete refrigerating machine, and, as in the case of incondensable gas, it is merely a motive-power heat-engine, absorbing heat at a low temperature and rejecting it at a higher, with the result that instead of the engine giving out power, power must be spent in driving it. In other words, the resulting power is a negative quantity, the formulæ applicable to a motive-power engine being equally applicable to a refrigerating machine.

If the natural temperature of the earth were about 200°, the steam-engine would become a very excellent refrigerating machine; but as the temperature of the earth is much below 200°, we must use a medium whose boiling and condensing temperatures under reasonable pressures are much lower than water. Sulphuric ether and ammonia have been most largely used, but other substances, such as sulphurous acid and light hydro-carbons, are employed.

There is a certain analogy between the action of gravitation and heat which may serve at least as an illustration. Thus when we raise a body in height, we must spend energy in proportion to the height. And *vice versâ*, when a body descends it is capable of giving out energy in proportion to the height through which it falls. Substitute temperature for height, and the analogy holds good. To raise temperature we must spend energy in proportion to the rise of temperature, and when temperature falls energy can be exerted in proportion to the fall in temperature.

It is to be remembered that in an abstract point of view it matters nothing what medium is used.

We will now proceed to describe, and that briefly, the actual arrangement of some refrigerating machines, commencing with those in which a condensable fluid is used.

The ether machine we will take first, as being very simple.

It consists of an ordinary double-acting pump, generally with ordinary pump-valves, arranged so as to have as little clearance as possible. The boiler is charged with ether, which, absorbing heat, boils and gives off vapour, and the lower the pressure in the boiler the lower is the temperature at which the ether boils. This vapour the pump draws off from the boiler through the suction-valve, and having filled itself compresses the vapour on the return stroke, till its pressure is raised to that of condensation at the lowest temperature at which the surface-condenser, into which it

is expelled through the delivery-valve, can be conveniently maintained. The condensed and liquefied vapour returns to the boiler by a small pipe, regulated by a stop-cock. It is essential that the ether should return to the boiler as a liquid, and to ensure this, the level of the liquid ether in the condenser must be kept above the outlet of the feed-pipe by which it is returned to the boiler. This is either done by the attendant or by a self-acting arrangement. In the boiler, the ether during its evaporation absorbs heat either directly from the substance or liquid to be cooled, or, as is often the more convenient arrangement, from an intermediate liquid which does not freeze at the temperature employed, and which, being pumped through pipes, forms a convenient medium for conveying heat from the substance to be cooled to the ether boiler where it is to be absorbed.

This boiler may be variously arranged to suit special purposes. Thus, when a liquid is to be cooled, it may be very like a tubular steam boiler, the liquid to be cooled being passed through the tubes. Were such a machine perfectly air-tight, and no lubricant required, no ether beyond the first charge would ever be necessary.

As you can well believe, this in practice cannot be realized. The temperature of evaporation of ether, when pure, is at 4°, under a pressure of about 2·6 inches of mercury, which may be taken as the lowest temperature it is practicable to produce by its evaporation, and the highest pressure that would be required, even in the tropics, to effect its condensation is about 36 inches. These are for pure ether, but in practice it is hardly practicable to go so low, as under so high a vacuum difficulties present themselves; air and lubricating material are sucked in, which deteriorate the ether. And although by stopping the feed the pure ether may be distilled over and condensed, and the remaining impurities afterwards allowed to run out of the boiler or evaporator, this is an operation that can scarcely be effected without some loss. Losses of ether also increase rapidly when the pressure of condensation is high.

Of the liquids employed, ether and volatile hydro-carbons are highly efficient when the difference of temperature required is not too great. With ammonia a very wide range of temperature is practicable; but as this last liquid possesses a peculiar property, by which mechanical compression and exhaustion can be dispensed with, chemical compression (if we may use such a phrase) being substituted, it will merit special illustration.

A machine on this principle was proposed by Mr. Carré in 1859. It is based on an experiment of Faraday's.

While experimenting on the liquefication of gases under the combined influence of pressure and cold, he placed in one of the branches of a strong U-tube of glass a body which, under the influence of heat, gave off a quantity of the gas he wished to liquefy. This was his compressor.

The other branch he placed in a freezing mixture. This was his condenser. Notably he placed in the tube a dry chloride of silver, which had absorbed a considerable quantity of ammoniacal gas. Heat being applied to the end containing chloride of silver, while the empty end was kept cool, he found after a little time in that end a liquid which was liquefied ammonia. He then observed that as the tube was allowed to cool the ammonia evaporated, and the gas was re-absorbed by the chloride of silver. Here was a refrigerating machine, for during its evaporation the ammonia must absorb heat. Thirty years elapsed before this property of ammonia was turned to account. Ammonia behaves in the same way with chloride of calcium, with charcoal, and with water. I have tried the experiment with the two former, but, being solids, I failed to make with them a practicable refrigerating machine, owing to their almost total absence of heat-conducting power and their sluggish action. Mr. Carré, by using water, which, from the mobility of its particles and the rapidity with which it could be heated and cooled, produced a practicable machine.

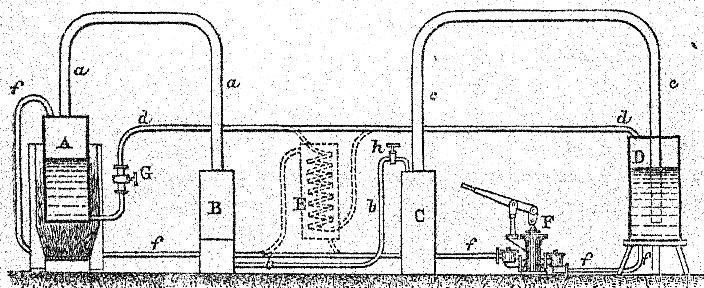
In its simplest form Carré's machine is intermittent in its action, and consists of two strong reservoirs, connected by a pipe—in fact, Faraday's U-tube—enlarged at each end. The larger end is a vessel about three-fourths filled with a strong concentrated solution of ammonia in cold water. When this is heated, and the smaller vessel placed in cold water, the ammoniacal vapour is expelled from the water, and, under the influence of cold and pressure, is condensed into a liquid in the smaller vessel. The hot water, or rather the hot weak ammoniacal solution left in the larger vessel, being now cooled by the application of cold water to the outside or otherwise, powerfully re-absorbs the ammoniacal vapour as fast as it is generated. Thus, the pressure being continually removed by absorption, the liquid ammonia boils in the smaller vessel, and this goes on as rapidly as we can cool the contents of the larger. Water, under the influence of heat and cold, performs the same function as the piston in the other machine, promoting the evaporation of the gas by creating a vacuum, and also compressing and condensing the gas, without the use of any mechanical arrangement. Although no engine in the ordinary sense is employed, energy, in the form of heat, is of necessity con-

sumed, and heat is absorbed at a low temperature and rejected at a higher, as in all other refrigerating machines. The range of temperature available is great, much greater than in the case of ether, for at the atmospheric pressure the boiling temperature of ammonia is—40° Fahrenheit. Usually the pressure required to liquefy the gas is about 150 lbs. per square inch. This is the simplest refrigerating machine made, but its intermittent action limits its use.

It, however, is easily transformed into a machine of continuous action, the operations being the same. But whereas in the intermittent machine there were two parts, each performing two functions, alternately at a high temperature and at a low one, we must now adopt four parts, each performing one function, and kept at one temperature.

As made by Messrs. Mignon and Rouart, of Paris, the parts consist of a boiler A (Fig. 3) in which the ammoniacal gas is distilled from

Fig. 3.



its solution, a condenser B to liquefy the gas, a volatiliser or boiler C in which the liquid ammonia boils and absorbs heat, and an absorber D into which the vapour as it is generated in C passes, and is absorbed by cold water.

These different parts are connected by, 1st, a pipe *a a* taken from the top of the boiler A to the top of the liquefier B; 2nd, a feed-pipe *b b* from the bottom of the liquefier B to the top of the volatiliser C; 3rd, a pipe *c c* taken from the top of the volatiliser C to the absorber D; 4th, a pipe *d d* taken from the bottom of the boiler A to the top of the absorber D; 5th, a tube *f f* taken from the bottom of the absorber D to the top of the boiler A. This apparatus is completed by a pump F in the circuit of the pipe *f f* from the absorber D to the boiler A, a cock G in the pipe *d d*, and lastly a cock H in the pipe *b b*.

The operations carried on in this apparatus are as follows: The

ammoniacal gas is distilled from its solution in water in the boiler A under a pressure in ordinary circumstances of about 10 atmospheres. The volatilised ammonia passes by the pipe *a a* to the liquefier or condenser B, which is kept cool by a supply of water. The ammoniacal gas being condensed in the liquefier B passes by the pipe *b b* to the volatiliser C, in which it boils and abstracts heat. As the liquefier or condenser is ordinarily at a pressure of about 10 atmospheres, while the volatiliser or boiler is at a pressure of about $1\frac{1}{2}$ atmosphere, the liquefied ammonia would rush at once through the feed-pipe *b b* were it not regulated by the cock H, so as to maintain at all times some liquefied ammonia in the condenser B. The ammoniacal gas, as fast as it is formed, passes from the volatiliser C to the absorber D, in which cold water absorbs it, compressing it in fact, and liquefying it, forming a solution of a convenient degree of saturation. This ammoniacal solution is returned to the boiler A, and the process is repeated. But in the course of distillation in the boiler, which must be performed quietly and without agitation, the solution of ammonia is found at the bottom to be comparatively poor; and while the strong solution from the absorber D is returned to the boiler A by the pump F, a corresponding amount of weak solution is drawn from the bottom of the boiler and returned to the absorber. The flow of this water is regulated by the stop-cock G. In order to prevent the great waste of heat, which was unavoidable in the intermittent machine, in cooling down the spent ammoniacal solution to enable it to act as an absorber, an interchanger is introduced, by which the heat of the spent solution, as it escapes from the bottom of the boiler A on its way to the absorber D, is given up to the strong solution on its way from the absorber D to the boiler A.

The heat interchanger, as is well known, consists of an arrangement of pipes through which the cold water passes in one direction, while the hot water passes outside these pipes in the opposite direction, or *vice versâ*. This interchanger is shown dotted in the diagram in the course of the pipe *d d*. Although by this apparatus loss of heat in heating and cooling the water of the solution as it passes from the boiler A to the absorber D, and *vice versâ*, is very largely avoided, the water passing to the absorber requires to be partly cooled by cold water. In this machine we have the motive power engine, which may drive the ether machine, or any other machine on the same principle as the ether machine, combined in one with the refrigerating apparatus.

Mr. Reece has introduced certain refinements by which somewhat more anhydrous ammonia is produced.

We come now to refrigerating machines in which the medium employed is air. Time will only permit us to describe, and that briefly, two machines, one with a regenerator and one without, which must serve as illustrations of machines of these, the two types into which air-machines may be broadly divided. Practically the employment of a regenerator is a more perfect way than compression and expansion of lowering the temperature of the air from that at which heat is rejected during compression to that at which it is absorbed during expansion, and *vice versâ*. I have shown elsewhere that the loss in using a regenerator need not exceed ½ per cent. of the heat stored up.[1]

The application of a regenerator to refrigerating machines unfortunately is limited. If the air used as the medium of producing cold contains moisture, that moisture is deposited on the meshes of the regenerator, and if the cold is sufficiently intense it freezes, and very speedily stops the passage of the air. Hence, unless the lowest temperature is above 32°, the air must either be perfectly dry so as to deposit no moisture, or the regenerator must be washed by a solution of salt and water, or its equivalent, which, while being cooled, will dissolve the snow and leave the regenerator clear.

As an example of a refrigerating machine with a regenerator, we shall take one I described fully before this Institution in 1874.[1] In this an enclosed quantity of air, at a pressure considerably above the atmosphere, is alternately compressed and expanded by the motion of a piston in a cylinder.

The operations are precisely those shown in Fig. 1, but instead of performing all the operations of heating and cooling in one vessel, we must in practice perform the compression A B at the higher temperature T^2 in a space kept at that temperature, and the expansion D C in another space kept at the lower temperature T^1. These two spaces are both formed in one cylinder, and are separated by a displacing piston, through which is a free passage, filled with layers of wire gauze, forming a regenerator. As this piston is shorter than the cylinder, when we move the piston upwards a space is formed between it and the bottom of the cylinder, and when we move it downwards an equal space is formed between it and the top of the cylinder. Thus, as we move the piston upwards and downwards, we shift the enclosed air from the upper space to the lower space, and *vice versâ*, the air passing freely through the regenerator. As the lower space has a free

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[1] Minutes of Proceedings Inst. C.E., vol. xxxvii., p. 244.

communication with a second cylinder and piston, by pushing its piston inwards while the regenerator piston is at its top stroke, we compress the air contained in the lower space, and by moving the regenerator piston to the bottom of its stroke, and allowing the piston of the second cylinder to recede, the air is expanded in the upper space between the regenerator and the top of its cylinder. The upper space is kept at the temperature T^1, and the lower at the temperature T^2. Thus the cycle consists of four operations.

1st. Isothermal compression from B to A in the lower space, rejecting heat at T^2, the regenerator being at top stroke.

2nd. Transference of the compressed air to the upper space by the regenerator and its piston moving downwards, and the air passing upwards through the regenerator leaving its heat stored up, and reaching the upper space at T^1.

3rd. Isothermal expansion above the regenerator in the upper space, accompanied by the absorption of heat at T^1.

4th. The regenerator and its piston moving upwards, and transferring the cold air through it to the lower space again. As the air passes downwards through the regenerator, it picks up the stored-up heat, and enters the lower space at the temperature T^2.

These operations are carried out by the compressing and expanding piston being connected to a crank and fly-wheel, the regenerator-piston being moved by a crank at right angles, or nearly so, to the compressing piston. Now the top and bottom of the regenerator cylinder are formed into a somewhat extensive cooling surface in order that the compression and expansion may be as nearly isothermal as possible, and it consists of circular water passages, through which water or brine circulates, and over which the air is caused to circulate rapidly. While the air expands in the space above the regenerator-piston it abstracts heat from a current of brine, which is being pumped through circular passages, and in the same way, while the air is being compressed below the regenerator-piston, the heat of compression is removed by water of the ordinary temperature circulating through a similar set of passages formed in the bottom of the cylinder.

The compression and expansion of the air when contained in the lower and upper spaces would be actually isothermal but for the extreme difficulty with which air is heated and cooled. To heat and cool air every particle of it must be made to come in contact with the substance which is to give or take heat from it.

Thus the surfaces of those substances must be extensive and subdivided, and, moreover, the air must be made to circulate over

them. All of these conditions are pretty fairly carried out in the arrangement shown. Still, with it all, there is no doubt that the temperature of the air inside the machine during compression is higher than the temperature of the water, and during expansion is lower than the temperature of the brine—to what extent I have never had the opportunity of ascertaining.

There is no adiabatic expansion or compression in this machine. The change of temperature as the air passes from compression to expansion is entirely affected by the regenerator, in which heat, in passing from compression to expansion, is stored up and again returned to the air, as it passes from expansion to compression. The action approximates pretty closely to the diagram, Fig. 1, only that the square corners there shown are by the continuous motions of both pistons rounded off.

In practice, this machine is made double-acting by another similar cooling cylinder, piston and regenerator being connected to the opposite side of the compressing cylinder.

In this apparatus the air may be used of any density the machine is strong enough to withstand. By using air of a high initial density, not only is the size of the machine reduced, but the efficiency of the heating and cooling surfaces of cylinders and of the regenerator become more efficient the higher the density of the air. Of course, this machine can practically only be used to cool a current of brine, or suchlike fluid, employed as an intermediary for abstracting the heat from the substance to be cooled, and delivering it up to the air in the machine. If we continue to work the machine without supplying heat from an exterior source during expansion, we will continue to lower the temperature until ultimately all the heat will be supplied to the cold end by conduction from the cylinder and piston and convection from the regenerator.

In a small model I have frozen mercury, and I have no doubt in a larger machine, where better precautions are taken, temperatures may be attained lower than anything that has yet been reached.

It is to be observed that the mechanical working of the machine is not affected by the temperature falling however low, for the compressing piston is all the time working at the natural temperature of the air, while the displacing piston is simply an easy working fit without friction.

Another modification of this machine consists of two double-acting cylinders, producing the same cycle of operations as were produced by the three cylinders described above.

For a more full description of its action I must refer you to the Paper I read before this Institution in 1874.

In this case the compressed air is cooled by the injection of cold water on the one side of the generator, while the expanding air receives its heat by cooling an injection of brine at the other side of the regenerator. Of course, the regenerator would speedily be closed up solid with snow were it not for the action of the brine injection, which, washing over the cold side of the regenerator, dissolves it as fast as it is formed. The action of the water in removing the heat, and of the brine in giving up heat to the air, is in this machine very nearly perfect from the extreme subdivision of the watery particles, spread as they are over the surface of the regenerator. The air and water are practically at the same temperature, and the compression and expansion isothermal. Of course, the lowest temperature to which this machine can be worked is limited to the lowest temperature to which the brine or solution of chloride of calcium can be exposed without freezing, but within these limits its action is very perfect.

Mechanically, too, the problem is very simple, for one cylinder is entirely hot while the other is entirely cold, and the packing of the plungers being constantly wet is easily kept air-tight.

In neither of the machines are there any valves opening or shutting. They may be likened to pumps for lifting heat from a low temperature to a higher, in which the regenerator performs the function of a valve, but of a valve which acts on heat, and prevents its return to the lower level or temperature at each stroke.

The last type of refrigerating machine I shall describe is that in which the working air cooled in the machine is discharged into a chamber, in order to cool it and its contents.

From its low specific heat and weight, unless the air is sent into the chamber considerably below the temperature of the chamber a very large volume must be passed through. Although some losses attend sending the air into the chamber at a temperature very much below that at which it is to escape, allowing it to be warmed up through a large range, this plan is generally found preferable to that of passing a very large volume through, with a small difference of temperature, as the latter involves much larger and more costly machinery with increased and serious losses from friction. In this way different parts of the chamber must of necessity be of very different temperatures, some at the temperature of admission, and some at the temperature of escape; but for the purposes to which such machines are applied this matters not; the temperature of escape is the important point.

Very early in the history of mechanical refrigeration, Professor Piazzi Smyth proposed to cool the air of rooms by compressing and cooling air, and subsequently expanding it, and discharging the air so cooled into a room, and along with the late Professor Rankine and Sir William Thomson had thoroughly investigated the subject, and carried out some experiments with a machine driven by hand.

Machines of this class in which air is merely compressed, cooled, expanded, and ejected, are inversions of Dr. Joule's air-engine, in which heat is rejected and absorbed at constant pressure, and differ essentially from those we have just described. In the latter, the working air absorbed heat during expansion, from the substance being cooled, which was converted into work as it was absorbed, and thus assisted to drive the machine. In the machines we have now under consideration no heat is absorbed by the air during expansion, and the heat is simply removed from the chamber as heat, and does not go to assist in driving the machine.

Its first introduction on a practical and efficient scale is due to Mr. Coleman, who applied it to the cooling of chambers for the preservation of meat.

The great difficulty which presented itself in all the earlier attempts was the great quantity of snow produced in the cooling cylinder, which involved not only a great waste of power, but introduced serious mechanical difficulties, choking up valve-passages and air-pipes. When we draw air from the atmosphere we cannot hope to get rid of the production of snow, although much can be done to reduce the quantity of water in the air before expansion or cooling takes place. In dealing with the large volumes of air, which we are compelled to do, the complete removal of moisture is out of the question. When, however, a machine is employed in which the compressed air is cooled without coming in contact with water, and which draws its supply of air from the chamber into which the cold air is discharged, the air in the chamber will soon cease to deposit more snow.

Machines of the kind we are describing may be broadly divided into two classes: those in which the compressed air is cooled by coming in contact with extensive metallic surfaces, kept cool by a current of water; and those in which the compressed air is cooled by being brought directly in contact with water by injection.

Mr. Coleman's machines on board ship are, in the best arrangements, worked by a compound surface-condensing engine, the compressing and expanding cylinders being in duplicate. Water is injected into the compressing cylinder, and also into the tower

or receiver, into which the air is compressed, cooling the air both during compression and after. To cool the air further it is conveyed by a pipe to the interchanger, composed of a nest of tubes, over the surface of which the air passes as it escapes from the chamber, and through which the compressed air passes and is cooled on its way to the expansion cylinders. From this a wooden trunk conveys the cold air to the meat chamber.

The importance of the interchanger may be illustrated thus: When the temperature of the chamber has to be kept below freezing, while the water outside which is available for cooling the compressed air is at say 90° Fahrenheit (not by any means an impossible case, passing through the tropics), very great loss would take place if the air from the chamber at probably 25° Fahrenheit were simply allowed to escape into the atmosphere. Even if this cold air were drawn directly into the compression cylinder, it would be at once warmed by the injected water, and after compression could not be lower than the natural temperature of the water, which we suppose to be 90°, and from which cooling by expansion would commence. The interchanger comes into play to obviate this loss. The compressed air, after being cooled as far as possible by water, is caused to pass through an extensive series of pipes, round the outside of which the cold air circulates as it escapes from the chamber. Thus if the currents of hot and cold air are made to traverse in an opposite direction, the escaping air will pass out at nearly the temperature at which the compressed air enters, while the compressed air will pass into the expanding cylinder cooled down to nearly the temperature at which the cold air escapes from the chamber.

In the case we have supposed, instead of expansion commencing from a temperature of 90°, it would commence from about 30°. In this respect it performs the same function as the regenerator did in the machines before described, and, like the regenerator, its effect is to reduce the necessary capacity of the cylinders. In practice, however, the interchanger cannot be made so efficient as this. In no case can it be allowed to cool below freezing, otherwise the moisture contained in the air would be frozen in the pipes and choke them up. When, as is generally the case, the compressed air contains moisture, the interchanger further performs the important function of condensing a large portion of it before expansion, which being drawn off, reduces the production of snow within manageable limits.

If dry compression is adopted, as in Mr. Haslam's machine, a cooling arrangement, like an ordinary surface condenser, is sub-

stituted for the injection of water, in order to cool the compressed air. No water is injected into the compressing cylinder, which is kept cool by a water-jacket, and of course must now be lubricated with oil. In every other respect the machines are substantially alike.

Where water injection is used in the compression cylinder, the compression is practically isothermal. Where dry compression is used the compression is, on the other hand, approximately adiabatic, and of course more power is consumed in compression, while less snow is produced; and in docks or rivers the air by which meat is frozen is not brought in contact with tainted water.

In Mr. Lightfoot's machine the moisture of the compressed air is further condensed by partial expansion, in what is equivalent to a primary expanding cylinder, the expansion being completed in a second one.

We will now notice some of the more important applications of the machines we have described.

Ice-Making.

Although not now the most important application of refrigerating machines, this was the earliest, and the first inducement to contrive such machines was the desire for ice and the high cost of it in the tropics. Dr. Gorrie's early machine was constructed for this purpose. The first attempts at making ice by refrigerating machinery consisted in filling a copper pan with fresh water, and immersing it in the cold brine which was cooled by the machine. Various ingenious arrangements whereby the pans containing the fresh water were gradually moved up towards the end of the trough or box at which the brine entered from the machine, and where it was coldest, were tried, but all the ice so made was soft and spongy, and more or less opaque in the centre of the block. This spongy part did not consist of hard solid ice, and on standing some little time became what is popularly called rotten, which really means that this part of the ice was spongy in texture, and as it melted the pores became filled with water. The consequence was, that the ice did not look well or keep well. In the course of experiments undertaken to get over this difficulty, I found that sound transparent ice was formed on the under side of a pan containing cold brine, whose bottom just touched the surface of the fresh water. As this worked out badly in practice, on pursuing the subject further, I found that it mattered nothing whether the cold surface on which the ice was formed was at the top of the water, at the bottom of the water, or immersed vertically in it,

the only condition necessary to produce solid clear ice being that the whole of the water was not frozen.

The shape these ice-making arrangements ultimately assumed in my hands was that of a large wooden tank, divided longitudinally by metallic slabs, placed vertically, forming internal passages through which cold brine from the machine was pumped. The tank was filled with fresh water, and as the cold brine circulated through between the plates forming the slabs, the ice formed on their outside grew thicker and thicker, but not so thick as to allow the ice on the adjoining slabs to join together. Thus a certain quantity of unfrozen water, like a mother liquor, remained between them. When the ice on two adjoining slabs was allowed to approach within 3 or 4 inches, I have put my hand down, and have felt the crystals of ice, which had begun to shoot across like spikes interlacing each other. Were this allowed to go on, these spikes would increase and interlace more and more, till ultimately the two slabs of clear ice would have grown into one, with spongy ice in the centre. By agitating the water between the ice slabs less space is required.

When not agitated, even perfectly transparent ice has minute straight holes in it, rudiments of the crystallization which I have described, at right angles to the surface on which it is frozen, and visible to the microscope, up which it is possible to pass a hair of the head.

For domestic sale the ice ought not to be less than 7 inches thick, while for the supply of steam-ships and suchlike it ought not to be less than 10 inches thick, and perfectly transparent.

After the brine has been shut off from an ice-box, there is sufficient cold stored up to increase the thickness of the ice $\frac{3}{4}$ inch. And indeed the best way of storing ice for short periods is to have plenty of ice-boxes, and leave the ice in them undisturbed. These boxes must be kept most carefully surrounded by a large thickness of non-conducting material.

After the large ice-blocks have been lifted from the boxes by a travelling crane, they are taken to a saw bench, and cut up into convenient sizes by a circular saw.

Cooling Paraffin.

In 1861 when I applied an ether machine to the cooling of paraffin oil, in order to extract the solid paraffin, it was, as far as I know, the first application of a refrigerating machine to manufacturing purposes.

Paraffin oil consists of a mixture of many oils of various specific gravities, and contains in solution many solid paraffins of different melting points, some crystallizing from the oil at a low temperature, and some at a comparatively high one. This crystallizable paraffin has to be extracted from the oil, as much to render the oil fluid at all ordinary temperatures, as to secure the valuable solid paraffin, which is so largely used for candle-making. As paraffin and paraffin oil are very bad conductors of heat, it was from the first evident that in cooling it artificially the heat to be removed could not pass through a layer of any considerable thickness but at a very slow rate. In my earlier arrangements, pipes closed at the bottom and open at the top depended vertically from an iron tube-plate, and by suitable arrangements a current of cold brine was maintained through these pipes. The pipes hung down into a wooden box, which was filled with paraffin oil, and after standing a certain time, the oil was cooled and the paraffin was crystallized from its solution in the oil, the whole forming a pretty firm pasty mass. An iron scraper plate fitted these tubes, and being attached to the box and drawn down with it as the box was lowered, forced this frozen paraffin down from between the tubes, and it fell into the bottom of the box. This arrangement worked until it was entirely burnt down. When it came to be reconstructed, I adopted a more speedy plan. I used a drum, with cold water circulating in it, or it might be cold brine, and as this drum revolved the lower part of its circumference dipped into a small pan containing the paraffin solution. A coating adhered to the drum, was cooled as the drum revolved, and on the opposite side was scraped off continuously, and fell into a tank below. By this means a continuous process was substituted for an intermittent one.

At the Oakbank Oil-works, the use of cold brine is dispensed with, and the drum itself is made the boiler or evaporator of an ether machine, only instead of ether a very volatile hydro-carbon, got in the works, is used.

An ammonia machine might be applied in the same way. The paraffin, as it is scraped off from the drum, falls into the trough, where it is slightly agitated, in order that it may be drawn off by a pump, and by that forced through filter presses, in which the solid paraffin is retained while the oil passes through the cloths. These presses are too well known to require description here, as they are used for many other purposes.

The application of water cooled artificially, instead of water at the natural temperature, in the coolers of breweries, need not detain us. Although there is nothing in the apparatus requir-

ing special description, this application of refrigerating machinery is one of vast importance. This is not a case where a low temperature is required; in fact, the lowest temperature is a good deal above freezing. But although a low temperature is not required, a great volume of heat has to be abstracted. As the volume of heat to be removed is great, but the difference of temperature is small, whatever the machine employed may be, it must be of large capacity, although the power required to work it is small. This is a case in which mechanical machines, by their necessarily large size and friction, in proportion to the small power required, work at a great disadvantage.

Preserving Meat.

To import meat in a frozen state from abroad has for years been the dream of many far-seeing men. The late Mr. Mort, of Sydney, devoted much attention to the subject of importing meat from Australia quite fifteen years ago.

The earliest plan of chambers for freezing or keeping meat was by circulating cold brine through pipes, or their equivalent, placed close to the ceiling. The first time I saw this plan adopted was by Messrs. Harris, in their curing-house, about 1862. Mr. Mort erected in Sydney an extensive cellar, cooled in this manner by an ammonia machine, in which to freeze freshly-killed meat, prior to its being put on board ship, while to carry off the steam from the meat as it cooled independent ventilation was provided. Showers or fountains of cold brine are more effective than pipes.

But although such arrangements are often very suitable on shore, it has been all along felt that such fittings were inadmissible on board ship. When a ship's hold is packed full of carcases, it is out of the question to have it traversed by inaccessible pipes or the like. Besides, such cargo can only be carried one way, and on the return voyage pipes would be an encumbrance, and liable to be broken.

The practical solution of the problem of importing meat from abroad is due to Mr. Coleman, who applied the direct method of cooling air which I have just described.

By this means all pipes and mechanical arrangements inside the meat chambers are dispensed with; the cold air simply passes by a wooden trunk along the top of the chamber, near to one side, with suitable distributing branches and holes, and escapes by a similar trunk near the other side. A snow-box is provided, some-

times outside, and in some cases inside the chamber, from which snow is removed periodically, but, notwithstanding, some accumulates among the carcases during a voyage. Of course, after the meat has been frozen and ceases to give off steam, or when it has been frozen before shipment, if the air is not cooled in contact with water the production of snow is less. The walls of the chamber are of wood, and double, the space being filled with a good non-conductor, such as charcoal, or dry hard wood shavings. This point of insulation is very important, but, like everything else on board ship, it becomes a compromise. The value of capacity limits the thickness of the non-conducting lining, and the machine has to be worked much more than it would if space for more thickness could be spared. Practically the walls do not exceed 12 inches thick.

In describing the machine, we spoke of its being generally more convenient to cool a small quantity of air to a low temperature in preference to a larger quantity to a higher temperature, and this applies very strongly to the case in point. Not only is the space on board ship limited (which renders smaller machines preferable), but the low temperature and increased density of the air render circulation amongst the carcases more efficient. The carcases having been frozen on shore in a separate establishment, and sewed up in cloth, being quite firm as they are put on board, can be stowed as closely together, one on the top of the other, as any other cargo, and the cold air, by its greater specific gravity, finds its way down through them. Attention has to be given during the voyage from time to time to see that the distribution of the cold air is equal throughout the chamber. For instance, if a ship has a steady inclination for some time to one side, the cold air will tend to that side; and to regulate this, thermometers are fixed in various parts of the chambers, accessible from the deck or from the air-trunks, by watching which the inlet apertures, by which the air escapes from the trunks, can be adjusted. For this purpose the trunks must be large enough for a man to pass freely through them.

On shorter voyages, such as those from America, it is not necessary to freeze the meat. All that is required is to keep it at a temperature just a little above freezing. In the longer voyages, from Australia and New Zealand, the meat must be frozen hard.

But besides their use in importing meat for sale, a not less important application of these machines on board ship is that of keeping an abundant supply of fresh meat and vegetables sufficient

for the voyage. Not only first-class passengers, but emigrants, and everyone on board ship, can now be supplied with fresh meat, and all the old horrors of scurvy are done away with.

To give an idea of the extent to which these machines have already been used, I have been at some pains to collect data which may be interesting.

Up to the end of 1883 I find that one hundred and twelve of these machines by various makers have been fitted on board ship, and fifty-nine for cooling meat on land.

To show how rapid has been the growth of the importation of dead meat by the help of these machines, I find that by Mr. Coleman's machine alone there has been imported from America in the last five years 563,568 quarters of beef, and 113,633 carcases of mutton.

During the last four years, by various machines, 3,159 quarters of beef and 138,664 carcases of mutton have been imported into London from Australia. And from New Zealand in the last two years 728 quarters of beef, and 129,732 carcases of mutton have been imported into London. In the months of January and February of this year, from Australia and New Zealand, 69,663 carcases of mutton have been imported.

Taking the beef and mutton at 6*d.* per lb., this represents a total value, in the years given above, of £3,477,417.

I need add nothing more to show the extreme value, not only to this country, but to our Colonies, of refrigerating machines. Already the trade in meat is, as you will see from the above figures, an extensive and important addition to our commerce. At present the process is practically successful, but there is no doubt room for improvement, probably in the machines themselves, probably in the arrangements on board ship, but certainly in more complete and extensive arrangements on shore for cooling the meat preparatory to its shipment, and for receiving it and storing it for sale after it is brought here.

Looking back we find refrigerating machines may be broadly divided into two classes, those in which cold is produced by the evaporation of a volatile liquid, and those in which it is produced by the expansion of air. Each has its appropriate use. For such purposes as making ice, in this country the ammonia machine will probably be chiefly used; while abroad, where supplies of chemical substances cannot at all times be had, and often only at an enhanced price, a machine producing cold by the expansion of air will be found preferable.

On the other hand, where water power can be had, the air-

machine, and machines after the type of the ether machine, are the ones applicable.

On board ship, as I have stated, the air-machine is the most suitable.

There is no doubt a large and increasing field for the employment of all of these machines, both in manufactures and in providing us with the necessaries as well as the luxuries of life.

Sir J. W. Bazalgette, C.B., President, said: In the address to which you have listened Mr. Kirk has put before you the salient points of the subject in language at once simple, clear, and convincing. When I entered this room this evening my motto would have been "Go Forward," but Mr. Kirk has convinced me to-night, in comparing the temperature at which heat is taken in and given out in thermo-dynamic engines as compared with refrigerating engines, that there is an advantage in sometimes going backwards. If you agree with this view, I will ask you not only to thank Mr. Kirk for the able lecture he has given, but to show him, by holding up your hands, that he has satisfied you that the ordinary adage about always going forwards is not invariably correct.

The resolution was carried unanimously, and acknowledged by Mr. Kirk.

3 April, 1884.

SIR J. W. BAZALGETTE, C.B., President,
in the Chair.

"Heat-Action of Explosives."

By Captain ANDREW NOBLE, C.B., F.R.S., M. Inst. C.E.

EXAMPLES of explosive substances will readily occur to all of you. The salient peculiarities of some of the best known may roughly be defined to be the instantaneous, or at least the extremely rapid, conversion of a solid or fluid into a gaseous mass occupying a volume many times greater than that of the original body, the phenomenon being generally accompanied by a considerable development of measurable heat, which heat plays a most important part not only in the pressure attained, if the reaction take place in a confined space, but in the energy which the explosive is capable of generating.

Fulminates of silver and mercury, picrate of potassa, gun-cotton, nitro-glycerine and gunpowder, may be cited as explosives of this class.

But you must not suppose that substances such as I have just named are the only true explosives. In these solid and liquid explosives, which consist generally of a substance capable of being burnt, and a substance capable of supporting combustion, in, for example, gun-cotton or gunpowder, the carbon is associated with the oxygen in an extremely condensed form. But the oxidisable and oxidising substances may themselves, prior to the reaction, be in the gaseous form; as, for instance, in the case of mixtures of air or oxygen with carbonic oxide, of marsh gas with oxygen, or of the mixture of hydrogen and oxygen forming water, which, if regard be had to the weight of the combining substances, forms an explosive possessing a far higher energy than is possessed by any other known substance.

But these bodies do not complete the list, and, under certain circumstances, many substances ordinarily considered harmless must be included under the head of explosives.

Finely-divided substances capable of oxidation, or certain vapours, form, when suspended in or diluted with atmospheric air,

mixtures which have been unfortunately the cause of many serious explosions.

Minute particles of coal floating in the atmosphere of coal-mines have either originated explosions, or in a very high degree intensified the effects of an explosion of marsh-gas. Flour-dust and sulphur-dust suspended in the air have produced like disastrous results. Lines of demarcation are generally difficult of definition, and the line between explosive and non-explosive substances forms no exception to the rule; but, from the instances I have given, you will note that an explosive may be either solid, liquid, or gaseous, or any combination of these three states of matter.

In the course of my lecture I propose, in the first instance, to give you a short account of the substances of which some explosives are composed, illustrating my meaning by giving you the composition of one or two which may be considered as types, and which are well known to you.

I shall, in the second place, show the changes which occur when our explosives are fired, and shall endeavour to give you some idea of the substances formed, of the heat developed, of the temperature at which the reaction takes place, and of the pressure realised, if the products of our explosive be absolutely confined in a strong-enough vessel, as well as of the experiments which have been made, and the apparatus which has been used either directly to ascertain or to verify the facts required by our theory.

I shall in certain cases suppose our explosives to be placed in the bore of a gun, and shall endeavour to trace their behaviour in the bore, their action on the projectile and on the gun itself. I shall, at the same time, describe to you the means and apparatus that have been employed to ascertain the pressure acting on the projectile and on the walls of the gun, and to follow the motion of the projectile itself in its passage through the bore.

Let us take, suppose at the temperature 0° Centigrade, and at the pressure 760 millimetres of mercury, two equal volumes of the gases, hydrogen and chlorine, which when combined produce hydrochloric acid. I have the gases in this tube, and let us apply a light; you will observe that the mixture explodes violently, with considerable evolution of heat. Now this is perhaps as simple a case of an explosive as we can have.

If we suppose the gases to be exploded in an indefinitely long cylinder, closed at one end, and with an accurately filling piston working in it, and if we suppose the gases (fired, you will remember, at 0° Centigrade, and atmospheric pressure) to be again reduced to the temperature and pressure from which we started,

the piston will descend to its original position, and the gases will occupy the same space as before they were exploded.

If we now suppose that we had, in a calorimeter, measured the quantity of heat produced by the explosion, that quantity of heat, about 23,000 gram-units per gram of hydrogen, or about 600 gram-units per gram of the mixture, expresses, without addition or deduction, the total amount of work stored up in the unexploded mixture, and from that datum, knowing the specific heat, we are able to deduce not only the temperature at which the explosion takes place, but the maximum pressure produced at the moment of explosion, and the work which the gases, in expanding under the influence of the heat evolved, are capable of performing.

If, instead of a single volume each of hydrogen and chlorine, we take two volumes of hydrogen and one of oxygen (which when combined produce water), or by weight two parts of hydrogen and sixteen of oxygen, and explode them as I now do, you will observe that there is a still more violent explosion, and I may add that there is a still greater development of heat.

If, as before, we supposed the explosion carried on in an indefinitely long cylinder, the piston, on the gases being brought back to the temperature and pressure existing before the charge was fired, would no longer stand at its original height, but at two-thirds of that height the three volumes would be condensed into two, and the heat determined by our calorimeter, about 29,000 gram-units per gram of hydrogen, about 3,300 gram-units per gram of the gaseous water produced by the explosion is increased above what may be considered the true heat of the explosion by the condensation which the aqueous vapour has suffered in passing from three to two volumes.

From the heat determined, however, we are able as before to deduce the temperature of explosion, the pressure exerted on the walls of a close vessel at the instant of maximum temperature, and the energy stored up in the exploded gases.

I have mentioned that the potential energy stored up in this mixture of hydrogen and oxygen is, if taken with reference to its weight, higher than that of any other known mixture, and it may fairly be asked why should such an explosive, whose components are so readily obtainable, not be more largely employed as a propelling or disruptive agent?

There are several objections, but you will readily appreciate one when I point out that if we assume a kilogram of gunpowder forming a portion of a charge for a gun, to occupy a litre or a decimetre cubed, a kilogram of hydrogen, with the oxygen neces-

sary for its combustion, would at zero and at atmospheric pressure occupy a volume sixteen thousand times as great.

Let us now pass to gun-cotton, known also as pyroxylin or trinitro cellulose. This substance, as you probably know, is prepared by submitting ordinary, but carefully purified, cotton to the action of a mixture of concentrated nitric and sulphuric acids at ordinary temperatures, where a proportion of the hydrogen in the cellulose is replaced by an equivalent amount of nitric peroxide.

Nitro-glycerine is in like manner formed by the action of a mixture of nitric and sulphuric acids on glycerine; but we shall for the present confine our attention to gun-cotton.

The formula representing gun-cotton is $C_6\ H_7\ 3\ (N\ O_2)\ O_5$, and gun-cotton itself may be employed in several forms in the flocculent or natural state, or it may be made up into strands, yarns, or ropes, or it may be granulated or made into pellets, or it may be highly compressed into slabs or disks, in which last form it is almost invariably used for industrial or military purposes, and for which we are so largely indebted to the labours and researches of my friend and colleague Sir Frederick Abel, C.B., Hon. M. Inst. C.E. Samples of all these forms are on the table before you.

When gun-cotton is fired, practically the whole of its constituents, which before ignition were in the solid, assume the gaseous form, and this change is accompanied by a very great development of heat. I now fire a train of different forms of gun-cotton, and you will note, in the first place, the small quantity of smoke formed, and this may be taken as an indication of the small amount of solid matter in the products of combustion. You will observe, also, that instead of the explosions which took place when our gaseous mixtures were fired, gun-cotton appears rather to burn violently than explode. This, however, is due to the ease with which the nascent products escape into the atmosphere, so that no very high pressure is set up.

Were we, by a small charge of fulminate of mercury or other means, to produce a high initial pressure, the harmless ignition that you have seen would be converted into an explosion of the most violent and destructive character.

You will finally note that this transformation differs materially from those which we have hitherto considered. In both of these the elements were, prior to the ignition, in the gaseous state, and the energy liberated by the explosion was expressed directly in the form of heat. In the present instance a very large but unknown quantity of heat has disappeared in performing the work of placing the products of explosion in the gaseous state.

Let me try to show you how large an amount of heat may be absorbed in the conversion of solid matter into the gaseous state.

You are aware that if a gram of carbon be burned to carbonic anhydride there are about 8,000 gram-units of heat evolved, whereas if a gram of carbon be burned to carbonic oxide, there are only evolved about 2,400 gram-units. Now *à priori* we may certainly suppose that the assumption by the carbon of the two atoms of the oxygen should result in equal developments of heat, but you will note, from what I have stated, that in the combination with the second atom of oxygen about two and a third times more heat is developed. Whence, then, comes the difference, and where has the heat disappeared which our calorimeter declines to measure? The missing heat may be assumed to have disappeared in performing the work of placing the solid carbon in the gaseous state.

In the case which we have been considering, the oxygen which supports the combustion of the carbon is already in the gaseous state; but with gun-cotton all the gases are, prior to combustion, in the solid state. Their approximate weights are exhibited in the following Table:—

TABLE I.—SHOWING the COMPOSITION and METAMORPHOSIS of PELLET GUN-COTTON.

Composition.		*Products of Explosion.*	
Carbon	24·89	Carbonic anhydride	0·424
Hydrogen	2·69	,, oxide	0·280
Nitrogen	13·04	Hydrogen	0·011
Oxygen	56·66	Nitrogen	0·145
Ash	0·36	Marsh gas	0·003
Moisture	2·36	Water	0·116
Formula $C_6H_7\,3(NO_2)O_5$.		Original moisture	0·021

Carbonic oxide and anhydride, nitrogen, hydrogen, aqueous vapour, and a little marsh-gas, are the products of explosion, and their quantities are such that a kilogram of gun-cotton, such as that with which Sir F. Abel and I have made so many experiments, will produce, when the gases are reduced to atmospheric pressure and to a temperature of 0° Centigrade, about 730 litres. In this volume the water produced by the explosion is not included, being at that temperature and pressure in the liquid form. In estimating either the pressure exerted on the walls of a close vessel, or the potential energy of the gun-cotton, we have to add to the work done, that is, to the heat absorbed by the great

expansion from the solid state into the number of volumes I have indicated, the potential energy due to the heat at which the reaction takes place.

As might be expected from the definite nature of the chemical constitution of gun-cotton, the constituents into which it is decomposed by explosion do not very greatly vary; the chief point to be observed being that the higher the tension at which the explosion occurs, the higher is the quantity of carbonic anhydride formed, that is, the more perfect is the combustion.

Gunpowder, the last and most important example I shall select, is also by far the most difficult to experiment with, as well as the most complicated and varied in the decomposition which it undergoes.

To begin with, it is not like gun-cotton, nitro-glycerine, and other similar explosives, a definite chemical combination, but is merely an intimate mixture, in proportions which may be varied to a considerable extent, of those well-known substances, saltpetre or nitre, charcoal and sulphur; and in this country the proportions usually employed are 75 parts of saltpetre, 10 of sulphur, and 15 of charcoal. They do not during manufacture undergo any chemical change, and it is perhaps owing to this circumstance that gunpowder has for so many generations held its place as the first and principal, indeed almost the only, explosive employed for the purposes of artillery and firearms.

One great advantage for the artillerist which gunpowder possesses in being a mixture not a definite chemical combination is, that when it is fired it does not explode in the strict sense of the word. It cannot, for example, be detonated as can gun-cotton or nitro-glycerine, but it deflagrates or burns with great rapidity, that rapidity varying largely with the pressure under which the explosion is taking place. As an instance of the difference in the rate of combustion due to pressure, we have found that the time necessary for the combustion of a pebble of powder in free air is about two seconds. The same pebble in the bore of a gun is consumed in about the $\frac{1}{200}$ part of a second; but a more striking illustration of the effect of pressure in increasing or retarding combustion is shown by an experiment devised by Sir F. Abel, and which by his kindness I am able to repeat. It consists in endeavouring to burn powder in vacuo, and you will see for yourselves the result of the experiment.

But although the composition of gunpowder is in this country approximately what I have said, the requirements or experiments of the artillerist have for certain purposes modified in a high

degree both the constituents and the physical characteristics of gunpowder.

In the following Table are exhibited the composition of the numerous powders with which Sir F. Abel and I have experimented; and the samples which I have upon the table, many of which will be new to some of you, illustrate the irregular forms into which we mould the mixture, which by a misnomer we still call gunpowder. Here you see the forms with which all are familiar, and which are called fine grain and rifled fine grain. Here, a little larger, you see rifled large grain, which at the introduction of rifled guns was the powder then used. Here these small lumps are called pebble powder, and this powder is that generally used in this country with rifled guns of medium size. Here is a still larger size of service pebble.

TABLE II.—SHOWING the COMPOSITION of VARIOUS GUNPOWDERS.

—	Powder "A."	Powder "B."	Powder "C."	Powder "D."	Cocoa.	Pebble W.A.	R.L.G. W.A.	F.G. W.A.	Spanish.	C. & H. No. 6.	Mining.
Saltpetre.	·8130	·7783	·6374	·7724	·7883	·7476	·7456	·7391	·7559	·7468	·6192
Sulphur .	·0018	·0028	·1469	·0615	·0204	·1007	·1009	·1002	·1242	·1037	·1506
Charcoal .	·1671	·1972	·2018	·1543	·1780	·1422	·1429	·1459	·1134	·1378	·2141
Water .	·0181	·0217	·0139	·0118	·0133	·0095	·0106	·0148	·0065	·0117	·0161

This form, prismatic, differing from the others chiefly from its regular shape, and from the hole or holes traversing the prisms, is perhaps the most convenient form in which powder can be made up in large charges, while these blocks exhibit still larger masses representing powders which have been used with success in very large guns. The object of the holes in the prismatic and other powders is to ensure the more complete combustion of powder by increasing the burning surface, as the prism is consumed, and consequently diminishes in size.

I draw your particular attention to these samples, because I shall have, before I conclude, something to say about them. You will observe that they are in the prismatic form, and that they differ from the other prisms, with which you can compare them, in being brown in colour instead of black.

Let us now apply a light to trains of different natures, and to some other samples of powder, experiments which I daresay at one time or another you have made for yourselves, and observe the result. You will note, in the first place, that an ap-

preciable time is taken by the flame to pass from one end to the other; but you will also note an essential difference between this combustion and that I showed you a short time ago with gun-cotton, viz., that there is a large quantity of what is commonly called smoke slowly diffusing itself in the air.

Now this so-called smoke is really only finely divided solid matter existing as a fluid, or volatilised only to a very slight extent at the moment and temperature of explosion, and if, adopting means which I shall presently describe to you, we had exploded in a close vessel the powder which we have just burned in the air, and allowed the vessel to stand for a few minutes, the products would be divided into two classes—one, a dense solid, generally very hard and always a disagreeably smelling substance; the other, colourless gases, the odour of which is, I must confess, not much more fragrant than that of the solid matter to which I have referred.

These large bottles on the table contain a portion of the so-called smoke of a charge of 15 lbs. of powder, collected in the manner I have described in a closed vessel. You will see it is a very solid substance indeed; but as these products are sometimes very protean in their characteristics, I have upon the table one or two other specimens of these residues differing considerably in appearance.

I have also in this steel vessel the products of combustion of 2 lbs. of powder. I shall not now let the gases escape; but after the lecture shall be glad to do so for the benefit of those who have no objection to a disagreeable smell.

If the gases produced by the combustion be analysed, they will be found to consist of carbonic anhydride, carbonic oxide, and nitrogen, as principal constituents, with smaller quantities of sulphydric acid, marsh-gas, and hydrogen with, this point depending much on the constitution of the charcoal, always small quantities, and occasionally considerable quantities of aqueous vapour.

The solid substances are found to consist of, as principal ingredients, variable quantities of potassium carbonate, sulphate, and sulphides, with smaller quantities of sulpho-cyanate, and ammonium sesquicarbonate.

The annexed Table shows by weight the products of combustion in the different powders examined by Sir F. Abel and myself, and I call your special attention to the considerable variations in the decomposition of powders which are intended practically to have the same chemical constitution.

TABLE III.—SHOWING the DECOMPOSITION of the POWDERS in TABLE II.

Nature of Powder.	Weight, Gaseous Products.								Weight, Solid Residue.										Total Weights.	
	Carbonic Anhydride.	Carbonic Oxide.	Nitrogen.	Sulph-Hydric Acid.	Marsh Gas.	Hydrogen.	Oxygen.	Water.	Potassium Carbonate.	Potassium Sulphate.	Potassium Hyposulphite.	Potassium Monosulphide.	Potassium Sulphocyanate.	Potassium Nitrate.	Potassium Oxide.	Ammonium Sesqui-Carbonate.	Sulphur.	Water Pre-existent.	Gaseous Products.	Solid Residue.
Powder A	·2253	·0529	·1158	..	..	·0022	..	·0225	·5474	·0017	·0048	·0034	..	..	..	·0058	..	·0181	·4187	·5812
„ B	·1915	·1014	·1200	..	·0019	·0042	..	·0026	·5296	·0006	·0008	·0006	..	..	..	·0240	..	·0217	·4216	·5773
„ C	·2723	·1315	·0875	·0191	·0056	·0011	..	..	·2036	·0042	·0073	·1646	·0187	..	..	·0081	·0627	·0139	·5307	·4692
„ D	·2467	·0529	·1188	·0091	·0006	·0011	..	..	·4579	·0230	·0029	·0382	·0005	..	..	·0016	·0352	·0118	·4409	·5591
Cocoa powder	·2198	·0086	·1049	..	·0004	·0006	..	·0832	·4360	·1332	..	..	..	..	..	..	..	·0133	·4175	·5825
Pebble W.A. means	·2685	·0477	·1123	·0111	·0006	·0006	..	..	·3258	·0710	..	·1042	·0014	·0013	..	·0005	·0445	·0095	·4409	·5496
R.L.G. W.A. means	·2630	·0422	·1117	·0109	·0008	·0009	·0002	..	·3415	·0844	..	·0807	·0013	·0015	..	·0004	·0490	·0106	·4298	·5591
F.G. W.A. means	·2689	·0355	·1123	·0101	·0004	·0007	·0003	..	·2861	·1252	..	·0999	·0007	·0009	·0056	·0003	·0381	·0148	·4282	·5569
Spanish	·2457	·0136	·1108	·0096	..	·0003	·0007	..	·2186	·2975	..	·0473	·0003	·0058	..	·0002	·0431	·0065	·3808	·6127
C. & H. No. 6	·2593	·0247	·1132	·0083	·0046	·0008	..	..	·3413	·1250	..	·0717	..	·0017	..	·0005	·0372	·0117	·4109	·5774
Mining	·2279	·1522	·0858	·0389	·0070	·0017	..	..	·1945	·0028	..	·1745	·0139	·0004	..	·0084	·0664	·0161	·5135	·4201

Considerations such as are suggested by this Table led Sir F. Abel and myself to make a statement which has been somewhat misunderstood, and which has been the subject of a good deal of controversy, viz., that, except for instructional purposes, but little accurate value can be attached to any attempt to give a general chemical expression to the metamorphosis of a gunpowder of normal composition.

Now by this statement, to which, after many years of research, we most emphatically adhere, we did not mean to say that, given precisely the same conditions the same products would not follow; but we did mean to say that the circumstances under which gunpowder, nominally of the same composition, may be exploded, are so varied—the nascent products may find themselves under such varied conditions both as to pressure, temperature, and the substances with which they find themselves in contact, this last point depending much on the physical characteristics of the powder—that it is not wonderful if considerable variations in the products ensue.

I need only refer in illustration of my remarks to the very interesting decomposition experienced by cocoa-powder. Observe the very small quantity of carbonic oxide, and the large quantity of water formed, while the solid constituents are reduced in number to two.

Let me now call your attention to another point. The Table giving the decomposition of gunpowders shows also the ratio between the weights of the solid and gaseous products; but it is necessary that we should know the volume of the gases at ordinary temperatures and pressure. A kilogram, then, of these powders, at a temperature of 0° Centigrade, and a barometric pressure of 760 millimetres, would give rise to the following quantities of gases:—The numbers in the Table expressing litres per kilogram, or cubic centimetres per gram of powder exploded.

TABLE IV.—SHOWING the VOLUMES of PERMANENT GASES EVOLVED by the COMBUSTION of 1 GRAM of the UNDERMENTIONED POWDERS:—

—	Powder "A."	Powder "B."	Powder "C."	Powder "D."	Cocoa.	Pebble W.A.	R.L.G. W.A.	F.G. W.A.	Spanish.	C. & H. No. 6.	Mining.
Vols. of gases	254	315	347	282	198	278	274	263	234	241	360

That is to say:—Assuming that a kilogram of each of these powders occupied a decimetre cubed, the figures in the Table represent for each description of powder the number of similar volumes occupied by the liberated gases when at the temperature and pressure I have named.

I have, in the case of each explosive that I have described, given to you the number of heat-units produced by the explosion. Following the same course with these powders, the number of gram-units of heat evolved by the combustion of a gram of each of the powders with which we have experimented is given in Table V.

TABLE V.—SHOWING the UNITS of HEAT EVOLVED by the COMBUSTION of 1 GRAM of the UNDERMENTIONED POWDERS:—

—	Powder "A."	Powder "B."	Powder "C."	Powder "D."	Cocoa.	Pebble W.A.	R.L.G. W.A.	F.G. W.A.	Spanish.	C. & H. No. 6.	Mining.
Units of Heat	800	715	525	745	837	721	726	738	767	764	517

As in the case of the quantity of gas, so with the heat evolved; there is a great and similar variation in the units of heat, but with this peculiarity—that the powders producing the largest quantity of gas invariably evolve the least quantity of heat.

Take for example the last six powders on our list, and observe that in every case the volume of the permanent gases is in inverse ratio to the units of heat evolved. In fact, if, as is done in Table VI., we arrange these six powders in descending order of the number of units of heat, and if we place them also in ascending order of the number of volumes of gas produced, it will be found that we have precisely the same arrangement.

TABLE VI.

Nature of Powder.	Units of Heat per Gram Exploded.	Cubic Centimetres of Gas per Gram Exploded.
Spanish pellet	767·3	234·2
Curtis and Harvey's No. 6	764·4	241·0
W.A. F.G.	738·3	263·1
W.A. R.L.G.	725·7	274·2
W.A. pebble	721·4	278·3
Mining	516·8	360·3

Let me dwell a little longer on this point. Take the powder which has developed the greatest amount of heat—the Spanish. Note that the amount of heat generated is about 50 per cent. greater than that developed by the lowest on the list—the mining. On the other hand, note that the volume of permanent gases evolved by the mining powder is about 50 per cent. greater than that given off by the Spanish.

The products of the volumes of gas and the units of heat evolved in these powders are nearly the same, and, indeed, the remark may be extended to the other powders in the list, the products of these two numbers not differing very greatly from a constant quantity.

You will anticipate the deduction I am going to draw from these singular facts.

Assume for a moment, for the sake of simplicity, that these six powders have the same composition, but that fortuitous circumstances—their physical condition, for example—have determined the varying quantities of gas evolved, and of heat developed. Assume further—the assumption approximating to the truth—that the potential energy of all the powders is the same, and we arrive at the conclusion that the smaller number of units of heat, which can be measured by our calorimeter in the case of the mining powder, is due to the larger amount of heat absorbed in placing the much more considerable proportion of the products of combustion in the gaseous condition.

Heat, then, plays the whole *rôle* in the phenomenon. A portion of this heat, to use the old nomenclature, is latent; it cannot be measured by our calorimeter; that is, it has disappeared or been consumed in performing the work of placing a portion of the solid gunpowder in the gaseous condition. A large portion remains in the form of heat, and, as we shall see later, plays an important part in the action of the gunpowder on a projectile.

Turn now to the temperatures and pressures which will be developed when the various explosives we have been considering are fired in a close vessel.

If we suppose the two first explosives described, viz., the mixtures of hydrogen and chlorine, and the mixtures of hydrogen and oxygen, to be at atmospheric pressures when fired, both the theoretic temperatures of explosion, and the resultant pressures may be affected to some extent by dissociation, which, I need hardly say, acts in the direction of reducing both the temperature and the pressure.

Little or nothing is known of the extent to which dissociation

takes place at the very high temperatures produced by the gases we are discussing. That extent, whatever it may be, will doubtless be largely reduced as the tension at which the explosion is carried on is increased.

If we suppose no dissociation to take place, and the gases to follow the laws of Boyle and Guy Lussac, a temperature of about 4,500° Centigrade will be reached by the explosion of the mixture of chlorine and oxygen, and a temperature of about 8,000° Centigrade by the mixture of hydrogen and oxygen, while the pressures reached will be respectively about 17 and 20 atmospheres.

You will note how feeble are the pressures compared with those with which we have to deal in the case of the explosives to which I now come. The mixed gases could, of course, prior to their detonation, be highly condensed, but the difficulties attending the use of such explosives in the condensed form, whether for artillery or industrial purposes, would be insurmountable.

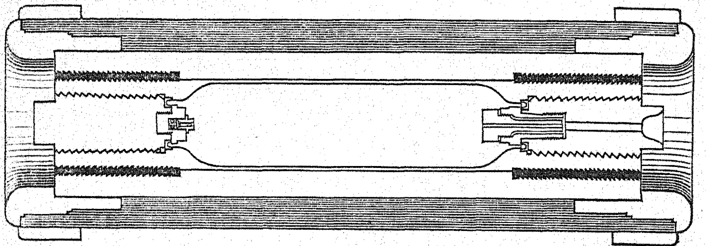
Before entering upon the temperatures and pressures developed by the explosion of gun-cotton and gunpowder, as the data I shall lay before you are chiefly derived from experiments made by Sir F. Abel and myself, it may be well to describe, as briefly as possible, some of the apparatus employed by us in our researches.

These diagrams (Figs. 1 and 2, p. 214) represent two of the vessels in which the explosions were made, one being a very large one, reinforced by steel ribbon, and open at both ends, the two open ends being closed by screw-plugs, the plugs themselves being fitted with special arrangements, with the details of which I need not trouble you, for preventing the escape of gas past the screws of the plugs. In one of the plugs is fitted a small instrument called a crusher gauge, the object of which is to determine the pressure existing in the chamber at the instant of explosion. In the other plug is fitted at will an arrangement by which the charge is fired by electricity without any communication with the external air by which the products of explosion can escape.

Although not belonging to my subject, I may here mention a very singular accident which on one occasion happened in using this vessel, and which explains accidents which have occasionally happened with the B. L. guns. I was experimenting with large charges of powder. The end of the vessel was placed against a wrought-iron beam. The screw—a half-inch pitch—being a very good fit, was screwed into its place with much difficulty, and with the use of a good deal of oil. On firing, the screw unscrewed, I need scarcely say in a very minute part of a second, until the last two threads were reached. These were sheared. Owing to the

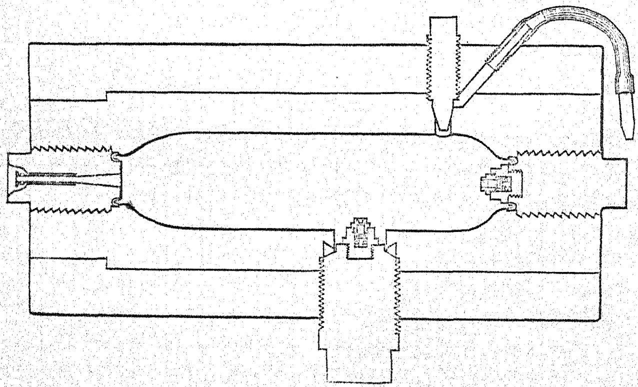
wrought-iron beam, which, by the way, the canted end of the screw knifed as neatly as if it had been done in a lathe, there was no motion of translation, but the motion of rotation was so high that the screw, first striking the ground and then an iron plate at an angle of 45°, went vertically into the air with a singular humming noise, descending in about thirty seconds a few feet from the place from which it rose.

Fig. 1.



Explosion-Vessel for Large Charges.

Fig. 2.



Vessel used for Experiment with Explosives.

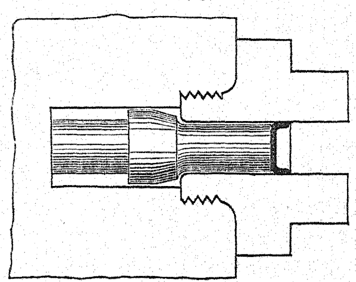
The accident, unexpected as it was, is not so difficult to understand if you remember that the screw was, so to speak, floating in oil, and that the expansion of the cylinder under the high pressure would remove nearly all the friction I have mentioned.

The other vessel is used for smaller charges, and you will observe that on it is shown the arrangement for letting the gases escape, either for analysis, measurement of quantity or other purposes.

It may serve to illustrate the progress that has been made in Artillery if I mention that thirty years ago the largest charge then used in any gun was 16 lbs. of powder. The 32-pounder gun, which was the principal gun with which our fleets were armed, fired only 10 lbs.; but I have fired, and absolutely retained in one of these vessels, no less a charge than 23 lbs. of powder and 5 lbs. of gun-cotton.

The gauge which I have called the crusher-gauge is here shown (Fig. 3). Its action is easily understood. The gas acting on the

FIG. 3.



CRUSHER-GAUGE.

surface of this piston crushes the copper cylinder on which the piston rests, and by the amount of the crush the value of the pressure can be determined.

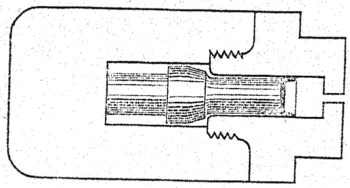
Under certain circumstances great care is necessary in the use of these gauges.

With gun-cotton, for example, with large charges, or high density of charge, or when the gun-cotton is detonated, the products of explosion may be projected with an enormous velocity against the piston. In such a case the pressure indicated would not be the true gaseous pressure—such I mean as would exist were the products of explosion retained in a vessel impervious to heat until the violent waves of pressure generated by the ignition had subsided—but to this true gaseous pressure would be superadded a portion of the energy stored up in the products of explosion which we may consider in the light of small projectiles striking the gauge and impressing their energy upon it. In our earliest experiments on gun-cotton our results, as far as pressure was concerned, were found to be valueless from this cause, and we resorted to various plans to avoid this inconvenience, the most effectual of which is shown here (Fig. 4, p. 216), the gases being admitted to act on the piston only through an exceedingly small hole, thus

shielding the piston from the waves of pressure to which I have alluded.

Even with gunpowder, if the pressures be very high, greater pressures than the true ones may be indicated from the energy imparted to the piston during the space it passes through in crushing the copper, and the most accurate results will be obtained if, prior to the experiment, the coppers be crushed to indicate a pressure a little short of that expected.

FIG. 4.



SHIELDED CRUSHER-GAUGE.

In most of the important experiments with gun-cotton a crusher-gauge with an unshielded head was placed at the further extremity from the point of ignition. The pressure indicated by this gauge denoted that due to the wave I have described. Two or three other gauges with shielded heads were employed in other portions of the cylinder to indicate the true gaseous pressure.

Let me give an example to show the effect of this arrangement.

A charge of about 3·5 lbs. of gun-cotton was fired in a cylinder with the crusher-gauges arranged as I have said. Two of the crusher-gauges admitted the gas to the piston through an aperture of only 0·01 inch in diameter; another admitted it through an aperture four times as great, or 0·02 inch in diameter, while the crusher-gauge exposed to the wave-action had its aperture of the full diameter.

The pressures indicated by the first three gauges were respectively 25·6, 26, and 27·1 tons on the square inch, but that given by the gauge at the end of the chamber indicated a pressure of about 45 tons on the square inch, or nearly 7,000 atmospheres. On another occasion the pressures indicated by the first three gauges were respectively 32·4, 32, and 33·8 tons per square inch, while the pressure indicated by the gauge exposed to the wave-action was 47 tons.

Again, when a charge of nearly 5 lbs. of gun-cotton was exploded, the pressures denoted were 45·4, 45·9, and 43·8 tons,

while that of the exposed gauge was 54 tons per square inch, or about 8,200 atmospheres.

Many more examples might be given, but I must not weary you with dry figures; my object in inflicting so many on you is to show that, where properly protected, the crusher-gauge may be relied upon to give very accordant results.

As might be expected from the very different quantities of heat developed by the explosion of different natures of gunpowder, to which I have recently drawn your attention, the temperature at which that explosion takes place likewise varies considerably.

Calculation places the temperature of explosion of ordinary English powder at a little above 2,000° Centigrade, and the direct experiments I have been able to make confirm this estimate. I have submitted to the action of large charges sheet-wire platinum and iridio platinum. In all cases the platinum showed signs of fusion; in one case—that of a powder known to produce a high temperature—the platinum was completely fused.

The temperature of explosion of gun-cotton is at least double that of gunpowder, and all the internal apparatus we have used bear notable signs of the extraordinarily high heat to which they have been exposed, as well as to the extreme violence of the reaction.

Platinum wire and sheet either disappear altogether or are found in minute globules welded on to the surfaces of the apparatus. The internal crusher-gauges and all projecting parts of the apparatus present, when considerable charges are used, a most extraordinary appearance. The temperature to which the cold surfaces are suddenly exposed develops on the surface a network of minute cracks which sometimes present the appearance of being filled up with fused steel.

When the charges are very dense, and, owing to that density, the transformation takes place with extreme rapidity, or when the gun-cotton is exploded by fulminate of mercury, it frequently happens that small portions of the surface are flaked off. Crusher-gauges are sometimes broken transversely, as are also the nozzles of any parts of the apparatus projecting into the chamber.

Portions of the apparatus, in no way exposed to the direct action of the gun-cotton, are sometimes fractured in the most singular manner; while the correctness of our assumption as to the violence of the internal disturbance—I mean as to the waves of pressure passing from one end of the chamber to the other, and giving rise to local pressure not directly dependent upon the temperature and the volume of gas evolved—is evidenced by the

internal gauges always showing unmistakable signs of having been knocked about with great force; a result which does not obtain when gunpowder is the explosive employed.

Crusher-gauges and other portions of our apparatus that have been damaged as I have described are on the table.

Let me draw your attention to some of the evils attendant upon a very high temperature of explosion.

I have described to you some of the more striking effects of the high temperature of the explosion of large charges of gun-cotton on surfaces exposed to its action. But even when these remarkable effects are not shown, as for example when smaller charges are employed, and the cooling influence of large surfaces has more influence, the surfaces still frequently show by minute globules of metal that they have been in a state of fusion, and these indications are quite perceptible with gunpowder as well as with gun-cotton.

The very high charges now employed (830 lbs. have been fired in a single charge from a 100-ton gun and 300 lbs. from a gun not quite 25 tons in weight), and the relatively very long time during which the high pressure and temperature of the explosion are continued, have aggravated to a very serious extent the evils due to erosion, and the consequent rapid wear of the bores of guns. I have mentioned that at the moment of explosion the surfaces of the gun in the vicinity of the charge are in a state of fusion. You will readily understand that heated gases passing over these fused surfaces at a high velocity and pressure absolutely remove that surface and give rise to that erosion which is so serious an evil in guns where large charges are employed.

Suppression of windage—that is, making the projectile an exact fit to the bore, does much to diminish, but will not remove erosion altogether. The importance of the subject led Sir F. Abel and myself to make special investigations into the erosive qualities of some of the powders with which we have experimented. As might be expected, the erosive effect varies in a very high degree with the pressure of the eroding gases, but we were hardly prepared for the great difference in erosive effect between powders varying but slightly in the pressures they generated. For example, the powder giving the highest destructive effect eroded steel under the same pressure between three and four times as rapidly as another powder capable of giving to a projectile the same ballistic effect.

The two tubes I hold in my hand show the comparative erosion of precisely similar charges of two several powders. You will have little difficulty, even from where you sit in observing the difference

in their erosive action. Unfortunately, so far powder-makers have not succeeded in giving us a powder at once suitable for artillery purposes and possessing the non-eroding quality so greatly to be desired.

As you will perhaps surmise, although erosion does not appear simply to depend on the temperature of explosion, the gunpowder which gives the least erosion is that which produces the largest quantity of gas and develops the least heat. With the same temperature of explosion to avoid serious erosion the pressure should be kept as low as possible; and before leaving this part of my subject it may not be out of place to enumerate one or two of the causes which have made gunpowder so successful an agent for the purposes of the artillerist, which have enabled it, the oldest of all explosives, to hold its own as a propelling agent against the numerous rivals with which modern science has so lavishly furnished us.

In the first place then, gunpowder, as I have already mentioned, is a mere mixture, not a definite chemical combination. The rapidity of its combustion, it is true, increases very rapidly with the pressure, but it is free, or nearly so, from that intense rapidity of action, and from those waves of local pressure which are so marked with gun-cotton, nitro-glycerine, and other kindred explosives, when fired in large charges.

2. The temperature at which the reaction takes place, although absolutely very high, is if compared with gun-cotton, for instance, very low; and this, as you will gather from the remarks I have already made, is a point of great importance when the endurance of a gun is taken into account.

It is perhaps hardly necessary for me to say that I am not one of those who advocate or recommend the use of gunpowder giving very high initial tensions. Did we follow such a course we should lose much and gain little. The bores of our guns would be destroyed in a very few rounds. There is no difficulty in making guns to stand pressures very much higher than those to which we normally subject them, but then they must be in a serviceable condition. Nine-tenths of the failures of guns with which I am acquainted have arisen, not from inherent weakness of the guns when in a perfect state, but from their having, from one cause or another, been in a condition in which they were deprived of a large portion of their initial strength.

If to these considerations I add that with a given weight of gun a higher effect can be obtained, if the maximum pressure be kept within moderate limits, I trust I have said enough to vindi-

cate the correctness of the course which the gun-makers of the world have, so far as I know, without exception followed.

Another advantage possessed by gunpowder over the class of explosives with which I am now comparing it, is the comparative slowness with which the pressure is produced. You are aware that the strength of a structure is much more severely tested when the load or strain to which it is subjected is applied suddenly; so far as my experience goes, guns do not, to any appreciable extent, suffer from the suddenness with which gunpowder tensions are applied, except in a few isolated cases of exaggerated wave-action. But there is no question in my mind that, unless some means of certainly moderating the violence of this action be discovered, both nitro-glycerine and gun-cotton would from this cause strain the structure of a gun in a higher degree than is due to the pressure actually applied. There is another advantage on which I shall have something to say when I come to the energy developed by gunpowder, and that is, its more uniform action, due to the presence of solid matter in a finely-divided form, which, acting as a source of heat, compensates for the cooling effect due to the work done by the expansion of the permanent gases.

The theoretic pressure developed by gun-cotton, the whole of the products produced by the explosion being in the gaseous state, is not difficult to calculate. For, having measured by simple means, which I shall not stop to describe to you, the gun-cotton being first exploded at a high pressure, and the gases suffered to escape into a gasometer, the measured quantity being subsequently reduced to 0° Centigrade and 760-millimetre pressure, and knowing, at all events approximately, the temperature of explosion, we are in a position to calculate the pressure at any assumed density.

It has been considered by some authorities that, seeing the high temperature at which the explosion of gunpowder and, in a much higher degree, that of gun-cotton takes place, the pressures indicated by theory will be much altered by dissociation. For example, that the carbonic anhydride will be split into carbonic oxide and oxygen. Let me point out that supposing such dissociation to take place, the resultant pressure will, as in every case of dissociation, be much reduced, notwithstanding that at ordinary temperatures and pressures the carbonic oxide and oxygen occupy a much larger volume than does their combination into carbonic anhydride.

The cause of this reduction of pressure is the heat absorbed by dissociation, and I should not now have alluded to the subject had

it not occasionally been assumed that dissociation might increase the pressure of fired gunpowder. This it can never do, and, seeing the influence that pressure may be taken to have in counteracting the effects of temperature with regard to dissociation, Sir F. Abel and I, although it is dangerous to be too dogmatical with respect to reactions occurring under conditions so enormously beyond the range, both as regards temperature and pressure, of ordinary experience, are inclined to think that both with regard to gun-cotton and gunpowder the effects of dissociation, if they exist at all, are practically inappreciable. At all events, the actual pressures as measured, both in the case of gun-cotton and gunpowder, are certainly not below those required by theory.

Another point requires mention. The explosion of gunpowder is generally, either in the bore of a gun or in a close vessel, extremely rapid; but rapid as it is, when small charges are fired in a large vessel, there is a considerable reduction of pressure from the cooling effect of the vessel, owing to the great difference of temperature between the ignited powder and the vessel.

With gun-cotton this difference is much more marked, both because the weight of the explosive employed in experiments is much less, and the temperature of explosion is much higher.

Between charges of a few ounces and a few pounds, for instance, of the same gravimetric density there is a very marked difference of pressure.

The actual pressure reached by the explosion of gun-cottons experimented with by Sir F. Abel and myself, assuming the gravimetric density of the charge to be unity, would be between 18,000 and 19,000 atmospheres, or say 120 tons on the square inch.

The pressure I have indicated has not, I need hardly say, been reached in our experiments, both because we should have had great difficulty in making a vessel to stand such pressures, and because charges of such density would not readily be placed in the vessels.

The highest pressure actually recorded with a density of 0·55 was a little over 70 tons on the square inch. The internal gauges were entirely destroyed by the explosion, and the pressure indicated by the gauge which was not destroyed in the vessel itself is subject to some deduction, due to the energy of the gases to which I have already more than once alluded.

The pressures attained by exploded gunpowder are not nearly so high.

Taking the same density of unity, the pressure in a closed

vessel with ordinary powder reaches about 6,500 atmospheres, or about 43 tons on the square inch. We have found it possible to measure the pressures due to the explosion of charges of considerably higher density, and have observed pressures of nearly 60 tons with a density of about 1·2, although the great difficulty of retaining the products of explosion of heavy charges of gunpowder—it is far easier to retain the products of explosion of gun-cotton than of gunpowder—makes the determination a little doubtful.

It is unnecessary to point out the great advantage, when violent explosions or disruptive effects are required, which gun-cotton and its kindred substances possess over gunpowder; on the other hand, gunpowder has as yet, despite some disadvantages, no competitor which can be compared with it as a propelling agent for artillery purposes; at all events, in cases where large charges are requisite.

We have now found, in the case of each of the four explosives which I have taken as types: First, the volume of the gases developed by the explosion; second, the amount of heat generated; third, the temperature of the various products; fourth, the pressure existing under given conditions of density. We are, then, now in a position, from the known laws of thermo-dynamics, to deduce theoretically what will be the energy developed if the products of explosion be allowed to expand to any given extent, and what will be the total work they are capable of performing if suffered to expand indefinitely.

The products of the combustion of the first three of my explosives being practically all gaseous, the same method of calculation would be followed in each case; and as this method in a much more complicated form has also to be employed in considering the expansion of gunpowder in the bore of a gun, I shall, in this part of my subject, confine my remarks to gunpowder as being at once the most difficult, the most suggestive, and the most important.

But before going to the theoretic considerations involved, you may desire to know whether any, and if so what, experimental means have been adopted to ascertain in a practical manner the energy developed by an explosive in the bore of a gun.

Now several means have been adopted for this purpose. One method has been to employ a gun of different lengths of bore, and by measuring the velocity of a projectile fired with a given charge from three different lengths, to deduce both the energies and the mean pressures giving rise to these energies.

Another method has been by certain arrangements, by the use, for example, of the crusher-gauges I have described, or by the use of similar instruments placed at different points along the bore, to ascertain by direct measurement the pressure existing at such points, and from these pressures to deduce both the velocity of the projectile and its corresponding energy at these points. The objection to this mode of procedure is that, although the crusher-gauge may, under ordinary circumstances, and with slow-burning powder, be relied upon to give very correct indications of pressure in the powder-chamber, it cannot be relied upon as accurate when the gases or other products of explosion are in rapid motion.

Suppose, for example, a crusher-gauge, or other similar instrument, to be applied at a point near the muzzle of a gun, when the projectile is passing at a very high velocity, say 2000 feet per second. Now it is obvious that the layer of gas in contact with the projectile is endowed with the same high velocity, and if it be diverted so as to act on a pressure-gauge, the pressure-gauge will indicate not only the actual gaseous pressure, but an unknown additional quantity due to the energy of the moving products of combustion.

It was from this cause, aggravated, no doubt, by a defect in his pressure-gauge, that Rodman, the pioneer of this mode of investigation, determined pressures, tolerably accurate, in the powder-chamber, but which along the bore were so much in excess of the truth that in some cases his pressures, plotted down so as to form a curve, indicated energies three times as great as those actually developed in the projectile.

A third method followed has been by means of a chronoscope, designed to measure very minute intervals of time, to ascertain the times at which a projectile passes certain fixed points in the bore.

From these data we may deduce the velocities at all points of the bore, and may again from them calculate the pressures necessary to produce them. As the chronoscope that has been used for these experiments has been often described, I shall not detain you by explaining either the mechanical or electrical portions of the instrument, but, as bearing on thermo-dynamics, I may mention an experience in my earlier investigations with this instrument which may be new to you, as it then was to me. I wished to dispense with the toothed gear for driving certain disks, and I had imagined if two sheaves or pulleys of equal size were connected by a belt so arranged that the belt would not slip on either sheave, that the two pulleys must then be rotating with the same angular velocity. Such, however, is by no means the case. In my own

experiments the velocities differed greatly. I supposed the fact to be altogether new, but, as sometimes happens to most investigators, afterwards found that the anomaly had been before observed, and was due to the elasticity of the driving-belt I used, and that the work impressed on the driving-wheel, but not communicated to the driven, was transformed into heat absorbed by and dissipated from the belt.

Returning now to the experimental methods I have described, I may say shortly that the whole of them have been followed, and the results obtained, subject to some anomalies, which I shall stop neither to describe nor explain, have been carefully compared, and have been found to agree in a most remarkable manner with the results indicated by theory.

And, for the sake of clearness, let me recapitulate the problem with which we have to deal. Suppose a charge of gunpowder placed in the chamber of a gun. Suppose the gravimetric density of the charge to be unity, that it is fired, that it be completely exploded before the shot be allowed to move, what, immediately prior to the shot being permitted to move, is the state of things in the powder-chamber?

Roughly speaking it is as follows:—

The products of explosion are divided into two classes of substances, about two-fifths by weight of the powder being in the form of permanent gases and three-fifths solid matter, the solid matter being perfectly liquid at the moment of explosion and in an extremely fine state of division. By the combustion is generated some 730 units of heat. The temperature of the explosion is about 2,200° Centigrade, or about 4,000° Fahrenheit, and the exploded powder exercises a pressure of about 6,500 atmospheres, or about 43 tons per square inch, against the walls of the chamber and against the projectile.

Let us now suppose that the projectile which we have hitherto supposed to be rigidly fixed is allowed to move; that is, that the products of combustion are suffered to expand, and let us consider what are the relations existing between the density of the gases, the pressure they exert, and the velocity of the projectile.

The first person who attempted to solve this question was Hutton. He, however, supposed, as it was not unnatural to do in the then state of knowledge, that the tension of the inflamed gases was directly proportional to their density and inversely as the space occupied by them. In other words he supposed that the expansion of the gases, while performing work, was effected without expenditure of heat.

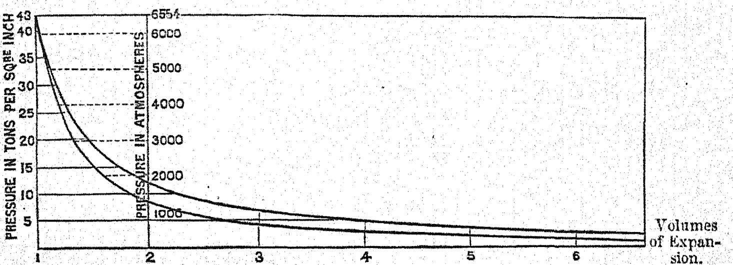
De Saint Robert, the first to apply to artillery the modern theory of thermo-dynamics, corrected Hutton's error, but like Hutton he supposed that the whole of the products of combustion were in a gaseous state, and as such doing work on the projectile.

Bunsen and Schischkoff, in their classical researches on gunpowder, pointed out that though a slight volatilisation of the solid products could not be denied, yet that it was in the highest degree improbable that the tension of such vapours would ever reach a single atmosphere, much less affect the pressures in any appreciable degree.

They therefore assumed that the work done on the projectile was due to the expansion of the gaseous products alone, without addition or subtraction of heat.

In the researches made by Sir F. Abel and myself, when we

Fig. 5.



Curves showing Pressure and Work developed by Expansion of Gunpowder, lower Curve denoting the Pressure on Bunsen and Schischkoff's Hypothesis.

found that the pressures in the bores of guns, and the energies generated by gunpowder, were far in excess of those deduced from Bunsen and Schischkoff's theory, we came to the conclusion that this difference was due to the heat stored up in the solid, or rather the liquid, products of combustion. In fact these products, forming as they do with ordinary English gunpowder, nearly three-fifths of the weight of the powder, being also in a state of very minute division, constitute a source of heat of a very perfect character, and are available for compensating the cooling effect due to the expansion of the gases on the production of work.

The formula expressing the relation between the pressure and the volume under these new conditions is of a rather complicated character, and instead of giving it to you, I have placed on this diagram (Fig. 5) a curve showing the relation between the tension and the density of the products of combustion when employed in

the production of work; and by way of showing you how important a part is played by the heat stored up in the solid residue, I have placed on the same diagram a curve showing the tension and the density calculated on Bunsen and Schischkoff's hypothesis; that is, that the energy of the projectile is due to the expansion of the gaseous products alone without addition or subtraction of heat.

You will observe that in this diagram the tension is represented by the ordinates, the expansions by the abscissæ, and the energy developed by any given expansion is denoted by the area between the corresponding ordinates, the curve and the axis of abscissæ.

If this theoretic curve be compared with the curve deduced from experiments in the bores of guns, after the charge may be supposed to be completely consumed, the agreement is most remarkable, and affords ample evidence of the approximate correctness of the theory. Were the curve derived from experiment to be laid down on this diagram, the curves, after, as I have said, complete combustion may be assumed to have taken place, are scarcely distinguishable.

In an earlier part of my lecture I stated that I could not agree with those who are in favour of the strongest—meaning by the term the most explosive—powder manufactured.

To show you the advance that has been made by moving in exactly the opposite direction, I have exhibited on this diagram (Fig. 6) two guns of precisely the same weight, but differing in date by an interval of ten years. One of these guns is designed to fire the old-fashioned R. L. G.; the other, modern powders.

Observe the difference in the appearance of the guns and in the thickness over the powder-charge.

These curves, you will note, represent the gaseous pressure at any point in the passage of the projectiles through the bore and their areas represent the total energies developed.

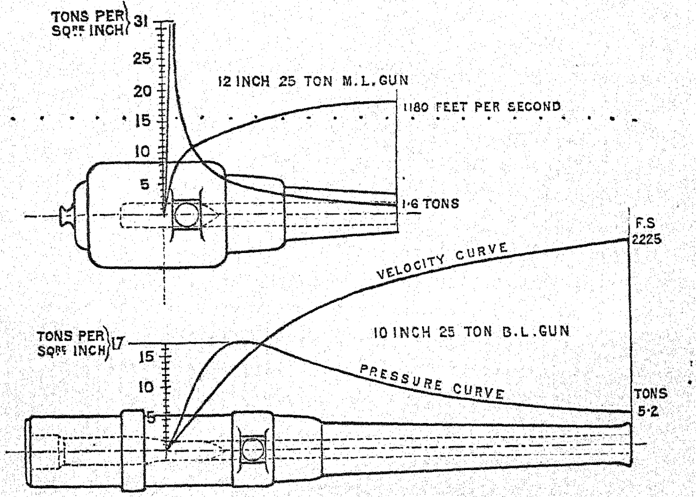
Observe the difference. The maximum pressure in the older is nearly double that in the modern gun, while the velocity developed by the latter is twice, and the energy not far from three times, that of the former; and if we take the foot-tons per inch of shots' circumference to represent approximately the respective penetrating powers of the projectiles, the superiority of the modern gun is still more apparent.

I am bound, however, to call your attention to one point. The new gun is, as a thermo-dynamic machine, much less efficient than the old. You will observe that the charge used with the new gun is just four times that of the old, while the energy realised is barely three times as great. This arises chiefly from the fact that although

the 10-foot gun is absolutely much longer than its rival, it is, taken in relation to the charge, much shorter; that is, the gases are discharged at the muzzle at a much higher tension.

If the modern gun were lengthened so that the products of combustion were discharged at the same tension, the difference in efficiency would be insignificant; and this you can readily understand, since, if we suppose the maximum tension in the modern gun increased to correspond with that in the old, the area indicated in the diagram would represent the additional energy to be realised by the use of an explosive powder; but this additional energy would be dearly purchased by the necessity of having to double the

FIG. 6.



COMPARISON BETWEEN EARLY RIFLED and MODERN RIFLED GUNS.

strength of the gun over the long space occupied by the powder-charge, and the same energy could be obtained in a much more economical way by adding two or three calibres to the length of the gun.

There is another point that must not be lost sight of. In my remarks on the explosion of gun-cotton, I drew attention to the effects which followed the waves of pressure resulting from the high velocity of the ignited products. With highly explosive powders, especially in long charges, similar effects are observed, and in such cases pressures have been registered very greatly above those due to the normal action of the charge, while these

abnormal pressures act during so short a time, that they produce an almost inappreciable effect upon the motion of the projectile.

The temperature of the gases of course suffers a considerable reduction during the expansion in the bore. If we suppose such a gun as I have been just describing impervious to heat, the loss of heat due to the work done would be about 400° Centigrade. It would be much greater were it not for the heat stored up in the non-gaseous products of combustion.

It remains to consider the total amount of energy stored up in our explosives.

For the first three we have discussed, the calculation is not difficult. Knowing the permanent gases formed, knowing also their specific heats at constant pressure and volume, the ordinary laws of thermo-dynamics enable us to calculate the total energy which will be developed.

In the case of the most important, gunpowder, the calculation is, as I have already pointed out, somewhat complicated by the non-gaseous products. But with this correction, the calculation for gunpowder also is reducible to the same law. (*Reverting to the diagram.*)

I have shown you that the energy available for any given expansion of a given weight of gunpowder is represented by the area continued between the curve, the axis of abscissæ and two ordinates, the initial, and that corresponding to the density at which the products of combustion are discharged from the gun.

The total energy obtainable if the charge be indefinitely expanded is represented by the area contained between the ordinate representing the initial pressure, the curve A B, and the axis of abscissæ, which is a tangent to A B at infinity.

Some interesting points may be noted in connection with the work developed by gunpowder.

The total energy stored up in gunpowder is about 340,000 kilogrammetres per kilogram of powder, or in English measure, a little under 500 foot-tons per lb. of powder.

If we compare this potential energy of 1 lb. of gunpowder with that stored up in 1 lb. of coal, we are, perhaps not unnaturally, being accustomed to the enormous pressures developed by gunpowder, somewhat astonished at the results of our comparison.

The potential energy of 1 lb. of gunpowder is as nearly as possible $\frac{1}{10}$ of that of 1 lb. of coal, and $\frac{1}{40}$ of that of 1 lb. of hydrogen. It is not even equal to the energy stored up in the carbon which forms one of its own constituents.

In making this comparison, however, one important point must

not be forgotten. Gunpowder and other kindred explosives have stored up in them the oxygen necessary for the oxidation of their carbon, and other oxidisable substances, while 1 lb. of carbon in burning to carbonic acid has to draw from the air nearly 3 lbs. of oxygen, and 1 lb. of hydrogen takes 8 lbs. of oxygen.

Many persons, deceived by the high pressures readily developed by gunpowder, have imagined that this or other similar explosives might be utilized as a motive-power, but the comparison I have made will have convinced you of the futility of any such attempts in an economical point of view.

For though, as I have stated, gunpowder contains the oxygen necessary for its own combustion, such oxygen is in a most expensive form, while the oxygen consumed by coal, being derived from the air, costs nothing; and if we take gunpowder as two hundred times more costly than coal, and as possessing only one-tenth of its potential energy, it follows that as an economic source of power coal has the advantage by at least two thousand to one.

I have stated that the total theoretic work of gunpowder is a little under 500 foot-tons per lb. of powder, but you may desire to know what proportion of this theoretic work is realised in modern artillery.

Dependent upon conditions with which I need not trouble you, the actual energy realised by modern guns varies from about 50 to a little over 90 foot-tons per lb. of powder, or, let us say, from about a tenth to about a fifth of the total theoretic effect. The total theoretic effect, you will remember, supposes infinite expansion, but if we compare the energy expressed in the projectile with that due to the expansion of the gases, we shall find that since a gun is an extremely simple form of a thermo-dynamic engine, the coefficient of effect is high. The average may, I think, be taken somewhere about 80 per cent. It rarely falls below 70 per cent., and is occasionally, with large guns and charges, considerably above 90 per cent.

But I must conclude both my own lecture and the series for this year.

I regret that it has not fallen to the lot of an abler and more practised lecturer to give the concluding lecture of a course on so important and interesting a subject as that upon which my predecessors and I have addressed you. None can be more painfully aware than I am that I have been unable to make my lecture worthy either of my subject or my audience, and I can only plead, in extenuation, that I had no idea that I was to be called upon until I saw my name announced to give the concluding lecture of

the course, and that business claims have utterly prevented my giving the time to the subject which its importance demands.

Were it necessary to urge upon your attention the claims of the modern science of thermo-dynamics, I might take, as perhaps the most striking instance, the progress of artillery during the last quarter of a century.

Twenty-five years ago our most powerful piece of artillery was a 68-pounder, throwing its projectile with a velocity of 1,570 feet per second.

Now the weight of our guns is increased from 5 tons to 100, the projectile from 68 lbs. to 2,000, the velocities from 1,600 feet to 2,000 feet, the energies from 1,100 foot-tons to over 52,000 foot-tons.

Large as these figures are, and astonishing as are the energies which in a small fraction of a second we are able to impress on a projectile of nearly a ton weight, they sink into the most absolute insignificance when our projectiles are compared with other projectiles, velocities and energies existing in nature, and with which we find ourselves surrounded.

Helmholz has given an estimate somewhere of the heat that would be developed if our earth were suddenly brought to rest, but if, looking at our earth in an artillery point of view, and following the principles I have to-night laid down, we considered our earth as an enormous projectile, and if we supposed further, that we could utilize the whole energy stored up in gunpowder, we should yet require a charge 150 times greater than its own weight, or 900 times greater than its volume, to communicate to the earth her motion in her orbit.

It only remains to me to thank you for the attention with which you have listened to a lecture which, from its technical nature, must necessarily be somewhat dry and uninteresting.

Sir J. W. Bazalgette, President.—It remains for me only to repeat what the gallant lecturer has reminded you of, that we have to-night arrived at the last of a series of most interesting lectures, and I venture to say that although this has been the last it has not been the least interesting. Our attention has been of late called very much to the subject of explosives, not only in time of war, but at home, and it behoves us as engineers to study the subject scientifically, and to know something of the materials which are used for such purposes. For my own part I must confess to a little feeling of nervousness when I saw our friend Sir Frederick Abel enter the room, but he has to-night treated us

very gently. I am sure you will agree with me that each of the gentlemen who have addressed us on their own particular branches of this subject has attained a very high position, not only from his abilities, but from the devotion of a life-time to study and experiment, and you will also agree with me that each of these gentlemen who has taken the trouble to concentrate the experience of a life-time, and to give it to you and me in one of these evening lectures, is deserving of our best thanks. I also venture to think that if any gentleman who has attended these lectures does not go away a wiser man than he was at the beginning of them, it has not been the fault of the lecturers. I am sure you will heartily agree to the proposal that we should first give a vote of thanks to Captain Noble for his most interesting lecture, and then we should give a combined vote of thanks to all the lecturers who have addressed us this session, and when I mention the names of Professor Osborne Reynolds, Mr. Wm. Anderson, Mr. E. A. Cowper, Professor Fleeming Jenkin, Mr. Kirk, and Captain Noble, I am sure those names will be sufficient to obtain a hearty response. (Carried by acclamation.)

Captain Noble: I suppose I have taken up enough of your time to-night, but I thank you very much on my own behalf, as well as on behalf of my distinguished predecessors.

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